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UTILITY PATENT APPLICATION TRANSMITTAL

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Attorney Docket No.	2981/USA/SMO/PJS
First Inventor or Application Identifier	Reimer, et al.
Title	Processing Apparatus Having Integrated Pumping System
Express Mail Label No.	EL233281193US

APPLICATION ELEMENTS
See MPEP chapter 600 concerning utility patent application contents

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   - Brief Summary of the Invention
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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of: Reimer, et al. Serial No.: N/A Filed: Herewith For: PROCESSING APPARATUS HAVING INTEGRATED PUMPING SYSTEM	Group Art Unit: N/A Examiner: Unknown **DATE OF DEPOSIT:** December 23, 1998 San Francisco, California

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United States Patent Application for:

PROCESSING APPARATUS HAVING INTEGRATED PUMPING SYSTEM

Inventors: Peter Reimer
Pedram Sabouri
Dennis Smith

Docket No.: 2981/USA/SMO/PJS

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PROCESSING APPARATUS HAVING INTEGRATED PUMPING SYSTEM

BACKGROUND

The present invention relates to an apparatus for processing substrates that has a pumping system for evacuating gas.

An apparatus **15** for processing a substrate **20** comprises process chambers **25a**, transfer chambers **25b**, and load-lock chambers **25c** mounted contiguously on a platform **28** with openings for transferring substrates between the chambers, as shown in Figure 1. In the process chamber **25a**, a process gas or plasma is used to etch features, deposit layers of material on a substrate **20**, or clean the chamber. The apparatus **15** is in a clean or semi-clean room **30**, and a pumping system **35** used to evacuate gas and maintain the chambers at a low pressure is in an adjacent room or basement. The pumping system **35** typically comprises a high vacuum pump **40**, such as a turbo molecular pump; a low vacuum pump **45**, such as a rotary blower pump; and a pre-vacuum pump **50a-c**, such as a dry vacuum pump. Typically, the inlet **55** of the high vacuum pump **40** is connected to the process chamber **25**, and its outlet **60** to a foreline **65** that extends from the chamber to the intake **70** of the low vacuum pump **45**, which in turn, is coupled to the intake of the pre-vacuum pump **50a**. The pre-vacuum pump **50a** exhausts to an exhaust scrubber **72**. The pre-vacuum pump **50a** reduces the pressure of the process chamber **25a** from atmospheric pressure (760 Torr) down to a pressure of about 0.01 Torr; the low vacuum pump **45** drops the chamber pressure down to about 0.0005 Torr; and only when the chamber pressure is below 0.1 Torr is the high vacuum pump **40** operated to achieve a high vacuum below 0.1 Torr down to 10^{-7} Torr. Another type of high vacuum pump is the cryo pump, which is used alone or in conjunction with the turbomolecular pump. A pre-vacuum pump **50** is also used in conjunction with cryo pump (not shown) to pump down the process chambers fast. Pre-vacuum pumps **50** and low vacuum pumps **45** are most commonly used in semiconductor processing apparatus; however, some semiconductor processing apparatus also use high vacuum pumps or cryo pumps in conjunction with the pre-vacuum and low vacuum pumps. A low vacuum pump **50** is essentially a pre-vacuum pump **45** whose

pumping performance is enhanced, for example, a pre-vacuum pump with an added blower can operate as a low vacuum pump **50**.

The forelines **65a-c** between the pumps **40**, **45**, **50a-c** and the chambers **25a-c** have a large diameter to provide a high conductance pathway that has a reduced pumping load and resistance. The low vacuum pump **45** and the pre-vacuum pumps **50** are large sized pumps that occupy volumes of from 0.5 to 1 m^3, large footprint 0.5m^2, and they are noisy and vibrate excessively during operation. That is why these pumps are typically located in a separate room below or adjacent to the clean room to save clean room space and to mechanically isolate the pump vibrations from the sensitive processing equipment. The distance between the two rooms can often require a 50 to 100 feet length of foreline **65a-c**. These extended lengths require that the forelines **65a-c** have a large diameter and low conductance to operate the low and pre-vacuum pumps with any reasonable efficiency. Typically, the foreline **65a-c** is a stainless steel pipe, which resists corrosion from the process gas, having a diameter of 50 to 100 mm (2 to 4 inches). However, the large diameter stainless steel pipe is expensive and a long length of pipe can cost as much as the pump itself. In addition, the large number of elbow joints and connections in the long foreline extending from the clean room to a separate room, have to be carefully sealed with non-corrodible gas seals to avoid leaks and releasing hazardous and toxic gases during operation, which further adds to large capital costs in semiconductor fabrication facilities. Also, the pipes are often heated to reduce the deposition of condensates on the inside surfaces of the pipes which wastes energy.

Furthermore, even with large diameter forelines **65a-c**, the efficiency of the low and pre-vacuum pumps **45**, **50a-c** is often decreased by a factor of 2 to 4 because of the loss in pumping efficiency caused by the large length of intervening pipeline. This is especially true when the chambers are pumped down to a low pressure mTorr range, where an increase in length of the forelines **65a-c** results in a large reduction in conductance. Another problem is that the large diameter and long length of the forelines **65a-c** provide a large surface area that serves as a heat sink upon which condensates are deposited from the process gas flowing in the lines. These condensates are dislodged and loosened by vibrations from the pumps **45**,

50a-c and back diffusion into the chambers **25a-c** to contaminate and reduce the yield of the substrates **20**.

Yet another problem of conventional apparatus arises because the pressure of gas in the chambers **25a-c** cannot be reduced in a responsive or fast manner. Typically, the chamber pressure is measured by the pressure gauge **80** which feeds a pressure signal to a throttle valve controller **90** which opens or closes the throttle valve **75a,b** to control the pressure of gas in the chamber **25a-c**. However, this system is slow to respond to pressure fluctuations caused by entry of substrates **20** in the chambers **25a-c**, transfer of substrates, or changes in a gas flow rate. In addition, the pressure reduction time obtained from "soft start" valves **76** are too slow. The soft gradual pressure reduction is used to prevent moisture condensation when lowering chamber pressure from atmospheric pressures to the mTorr range, by using two different size valves **76**. A smaller valve opening having a low conductance is opened when pumping the chamber down from one atmosphere to about 100 to 300 Torr, and a large sized valve is opened when pumping the chamber down to lower pressures. The two-cycle process provides a soft or gradual reduction in chamber pressure in stages that minimizes moisture condensate in the chambers **25a-c**. However, the time for pressure reduction during the small valve opening step of the process is often excessively long for high throughout fabrication processes.

Thus, it is desirable to have a semiconductor processing apparatus having a pumping system that does not require excessively long forelines with large diameters to operate efficiently. It is also desirable to have a small pump having reduced vibrations and noise for use in a clean room environment. It is further desirable to reduce the diameter, surface area, and length of the forelines between the chambers and the pumping system. It is also desirable to control the pressure in the chamber by means other than valves to increase response time and reduce particles. It is also desirable to more closely follow the pressure reduction versus time curve in the chamber to reduce pump down time. It is also desirable to reduce power consumption, cooling water consumption, and the release of heat within the clean room environment. It is also desirable to achieve all of the above with a small pump operating with a rotational speed of less than 10,000 revolutions per minute in order

to minimize time for pressure adjustment; minimize noise, vibration, and power consumption; and maximize bearing lifetime and pump reliability.

SUMMARY

The present invention is to a semiconductor processing apparatus for processing a semiconductor substrate, having a pumping system with high operating efficiency, small size, and low vibrational and noise levels. In one aspect, the present invention comprises an apparatus for processing a substrate using a chamber, such as a load-lock chamber, transfer chamber, or process chamber. A pump is adjacent to the chamber, the pump having an inlet connected to the chamber for evacuating gas in the chamber and an outlet that exhausts the evacuated gas to atmospheric pressure. A foreline can extend between the inlet of the pump and the chamber, the foreline preferably having a length of less than about 2 m and a diameter of less than about 80 mm. Alternatively, the apparatus is substantially absent a foreline between the inlet of the pump and the chamber. Preferably, the pump comprises a pre-vacuum or low vacuum pump.

In another aspect, the present invention comprises an apparatus for processing a substrate, the apparatus comprising a chamber, a pump, and a pressure controller for controlling a gas pressure in the chamber by providing a signal in relation to the gas pressure to a pump controller that changes the speed of the pump in relation to the signal. In use, gas is evacuated from a chamber by the pump and the pressure of the gas in the chamber is regulated by adjusting a speed of the pump. In a process chamber, a substrate is placed on a support in the evacuated chamber, gas is introduced into the chamber and optionally energized to process the substrate, and the pressure of the gas in the chamber is regulated by adjusting a speed of the pump.

In yet another aspect, the present invention comprises an apparatus for processing a substrate, comprising a pump having a plurality of inlet ports, a first inlet port provided to evacuate gas from a first chamber or first pump, and a second inlet port provided to evacuate gas from a second chamber or second pump. Preferably, the first and second inlet ports are connected to one or more inlet stages of the pump.

In another embodiment, the apparatus comprises a plurality of chambers having enclosures shaped and sized to hold one or more substrates, and a pump having a first inlet port in a first inlet stage, and a second inlet port in a second inlet stage, the first inlet port provided to evacuate gas from one chamber or pump, and the second inlet port provided to evacuate gas from another chamber or pump. Preferably, the plurality of chambers are mounted on a single platform, and the pump abuts the platform.

DRAWINGS

These and other features, aspects, and advantages of the present invention will become better understood with regard to the following description, appended claims, and accompanying drawings which illustrate examples of preferred embodiments of the invention, where:

Figure 1 (prior art) is a schematic view of conventional semiconductor processing apparatus for processing a substrate showing multiple chambers connected to a pumping system comprising high vacuum pumps, low vacuum pumps, pre-vacuum pumps, and an exhaust scrubber;

Figure 2 is a schematic view of a semiconductor processing apparatus according to the present invention showing chambers having abutting or adjacent pre-vacuum pumps that are substantially absent long forelines, too many valves;

Figure 3 is a graph showing the specific foreline conductance for increasing gas pressures and for different pipe diameters;

Figure 4 is a graph showing foreline conductance, chamber and valve conductance, and the total conductance for increasing flow rates of gas in a chamber;

Figure 5 is a graph showing the required pump capacity (or pumping speed) of a local pump without a foreline, a pump having a short foreline, and a remote pump having a long foreline, as a function of gas flow rate for maintaining the same chamber pressure;

Figure 6 is a graph showing the increase in deposition surface area of the internal surfaces of a foreline pipe as a function of its length and diameter;

Figure 7 is a graph of the measured pressure in a chamber for increasing gas flow rates showing the improved processing window obtained by a local pump versus a remote pump;

Figure 8a is a schematic side view of a low vacuum pump having an auger screw on a shaft;

Figure 8b is a schematic side view of a low vacuum pump having a roots-type mechanism;

Figure 8c is a schematic side view of a low vacuum pump having a rotor with an interdigited hook and claw assembly;

Figure 8d is a schematic side view of a low vacuum pump having an interdigited tongue and groove assembly;

Figure 9 is a graph of chamber pressure versus pumping time for different pump down cycles comparing local and remote pumping systems for a given chamber size;

Figure 10 is a graph showing a computer-generated model of an optimal pressure reduction curve to avoid ice condensation in a chamber, and various chamber pressure reduction curves obtained for different sets of selected pump speeds;

Figure 11 is a graph of the electrical power consumption of a pumping system showing the energy savings obtained during a typical pump down operating cycle;

Figure 12a is a schematic diagram of a semiconductor processing apparatus of the present invention showing multiple chambers connected to different stages of a single pre-vacuum pump;

Figure 12b is a sectional schematic side view of the pre-vacuum pump of Figure 12a showing a plurality of inlets ports and inlet stages; and

Figure 13 (prior art) is a schematic diagram of a conventional semiconductor processing apparatus showing multiple chambers that are each evacuated by separate pumping system.

DESCRIPTION

An exemplary apparatus **100** according to the present invention for processing a substrate **20**, such as a silicon wafer, is illustrated in Figure 2. The apparatus **100** comprises a platform **105** having a plurality of chambers each of which are shaped and sized to hold or enclose one ore more substrates **20**. The chambers are interfaced to one another and typically include load-lock chambers **110**, a transfer chambers **115**, and process chambers **120**, that are mounted contiguously with openings to transfer substrates therebetween. The load-lock chambers **110** hold cassettes that contain batches of substrates **20**. The centrally located transfer chamber **115** comprises a robot arm **118** which picks up and transfer substrates **20** from the cassette in the load-lock chamber **110** into a process chamber **120**, and after processing of the substrate in the chamber **120**, transfers the substrate to other process chambers (not shown) on the platform **105**. When the substrate **20** has finished processing, the robot **118** picks it up from the last process chamber and transfers it to another load-lock chamber (not shown) reserved for unloading. Although the present invention is illustrated by an apparatus for processing substrates, such as semiconductor wafers, the invention can also be used for processing other substrates, such as flat panel displays, circuit boards, and liquid crystal displays, and in other chambers as apparent to those skilled in the art and without deviating from the scope of the invention.

The process chamber **120** forms an enclosure for a support **125** for supporting a substrate **20**, such as a semiconductor wafer. The substrate **20** is held on the support **125** by an electrostatic chuck **130**. Metals commonly used to fabricate the process chamber are for example, anodized aluminum, stainless steel, INCONEL™, silicon oxide, boron carbide, or aluminum oxide. The support **125** is

typically made from aluminum with an anodized coating resistant to corrosion in the process gas. A process gas distributor **135** comprises a plurality of nozzles that are spaced apart and distributed to flow process gas around the substrate **20**. The process gas is supplied from one or more process gas supplies **136** via process gas lines **138** and their flow rate regulated by flow control valves **140**. The process gas is energized to process a substrate by a process gas energizer that couples electromagnetic RF or microwave energy to the process gas to form an energized process gas or plasma. The process gas can be activated in the chamber **120** by inductive coupling by applying an RF current to an inductor coil (not shown) encircling the chamber. In the embodiment shown in Figure 2, the process gas is energized by capacitive coupling RF energy to process electrodes in the chamber **120**. Preferably, at least a portion of the support **125** comprises an electrically conductive metal electrode that is chargeable to serve as the process electrode. A partially facing conducting or semiconducting portion of a ceiling **145** of the chamber serves as the other process electrode. The frequency of the RF applied to the process electrodes is typically about 50 KHz to about 60 MHZ, and more typically about 13.56 MHZ. The RF voltage applied to the process electrodes is at a power level of from about 100 to about 2000 Watts; and/or an RF current at a power level of from about 750 to about 2000 Watts is applied to the inductor coil.

In operation, one or more substrates are placed in the process chamber **120** which is evacuated by a pumping system **155**. The process chamber **120** can be used to deposit material on a substrate **20** such as by chemical or physical vapor deposition or etch layers on the substrate. Chemical vapor deposition processes that can be performed in the apparatus **100** to deposit coatings on the substrate are generally described in VLSI Technology, 2nd Ed., Ed. by Sze, McGraw-Hill Publishing Co., New York, which is incorporated herein by this reference. For example, typical CVD processes for depositing SiO_2 use a silicon source gas, for example SiH_4 or $SiCl_2H_2$, and an oxygen source process gas such as CO_2 and H_2O, or N_2O; or a process gas containing both silicon and oxygen such as $Si(OC_2H_5)_4$. Si_3N_4 is deposited from gases such as SiH_4 and NH_3 or N_2. Other commonly used process gases include NH_3, WF_6, and SiH_4. The apparatus can also be used for etching dielectric and metal layers, as generally described in VLSI Technology by S.M. Sze, McGraw-Hill Publishing Company (1988), which is also incorporated herein by

reference. Typical metal etching processes use gases such as HBr, BCl_3, Cl_2, HCl, SF_6, CF_4, and CHF_3. Resist stripping processes use O_2 and other gases to strip resist from the substrate. Cleaning gases for cleaning the chamber include NF_3 and CF_4.

An integrated and locally positioned pumping system **155** evacuates and exhausts the gas from one or more of the chambers. The load-lock chamber **110** is evacuated each time a new batch of substrates is placed in or removed from the chamber. Generally, the transfer chamber **115** containing the robot arm **118** is maintained at a low pressure during the entire processing sequence. The process chamber **120** is evacuated before introducing process gas in the chamber to process the substrate **20**, after processing of the substrate, and during cleaning by cleaning gas. The pumping system **155** can comprise separate pumps for each chamber, assemblies or sets of pumps, or a single pump for multiple chambers, as described below.

A preferred integrated pumping system **155** for the process chamber **120** comprises a high vacuum pump **160** and a pre-vacuum pump **165a** – both of which are positioned locally in the immediate environment around the chambers, as shown in Figure 2, and not in a separate or distal environment. In one embodiment, the pumping system **155** comprises a pre-vacuum pump **165a** adjacent to or abutting the chamber, having an inlet **170a** connected to the chamber to evacuate gas from the chamber, and having an outlet **175a** that exhausts the evacuated gas to atmospheric pressure via an exhaust scrubber **180**. The pre-vacuum pump **165a** is capable of evacuating the gas in the chamber **120** from atmospheric pressure to a pressure of less than about 10^{-2} Torr range. In addition, the high vacuum pump **160** is provided to drop the chamber pressure down from the low pressure range to high vacuum of 10^{-3} Torr range. The high vacuum pump **160** has an inlet **182** connected to the chamber and an outlet **185** that exhausts directly to the pre-vacuum pump **165a**. The high vacuum pump **160** is capable of evacuating the chamber from a pressure of about 10^{-2} Torr to a pressure as low as about 10^{-9} Torr, and it cannot exhaust gas to atmospheric pressure. Also, the high vacuum pump **160** can only operate within a narrow and low pressure range and cannot pump down the chamber from atmospheric pressure. Only after the pre-vacuum pump **165a** pumps down the

chamber to a low pressure can the high vacuum pump **160** be operated to further reduce the chamber pressure to ultra-low pressures.

Generally, the load-lock chamber **110** and the transfer chamber **115** do not need a high vacuum pump **160** because they do not need to be pumped down to a high vacuum. Thus, these chambers have only a pre-vacuum pump **165b,c** having an inlet **170b,c** connected to one of the chambers **110**, **115** for evacuating the gas from the chamber and an outlet **175b,c** that exhausts the process gas directly to atmospheric pressure via the exhaust scrubber **180**. The transfer chamber **115** has a short length of foreline **190b** or has no forelines between the inlet **170b** of the pre-vacuum pump **165b** and the chamber **115**. The load-lock chamber **110** has a short length of foreline or does not have any forelines **190a,b** between the inlet **170c** of the pre-vacuum pump **165c** and the chamber **110** because the pump is connected directly to and abutting the load-lock chamber **110**.

It has been discovered that the process efficiency and pump down time of the chambers can be substantially improved by changing the configuration and location of the pumping system **155** relative to the chambers **110**, **115**, **120**. In one aspect, the apparatus of the present invention comprises a short length of foreline **190a,b**, or no foreline at all, between the chambers **110**, **115**, **120** and their associated pumps **165b,c** or set of pumps **160**, **165a**. For example, in the exemplary process chamber of the apparatus, a foreline having a length of about 0.5-2.0 m extends from the pre-vacuum pump **165a** to the process chamber. The inlet of the high vacuum pump **182** is connected to the chamber, and its outlet to the foreline. In the transfer chamber, the pump is connected directly to the transfer chamber with or without a foreline having a short length of 0-2.0 m. For the load-lock chamber, the pre-vacuum pump **165c** is coupled to the chamber with or without any foreline. Preferably, the inlet between the pump feeds to the chamber through a short foreline having a length of less than about 2.0 m, and more preferably less than 0.5 m.

It has been discovered that the losses in pumping efficiency obtained are largely due to the losses in pumping conductance that arises from a long length of foreline between the pump and the chamber, as shown and described for a conventional apparatus in Figure 1. Figure 3 shows the specific conductance of

foreline pipes for increasing gas pressure in a chamber and for different foreline pipe diameters. For a given foreline pipe diameter, as the gas pressure increases, the specific conductance of the foreline does not change from gas pressures of about 0.1 to about 1-10 mTorr, and thereafter, the specific conductance increases sharply for increasing gas pressure. However, as the foreline pipe diameter increases from 5 to 250 mm, the average chamber pressure at which the specific conductance begins to increase, drops down from 10 mTorr down to 1 mTorr. For example, Figure 3 shows that at an average foreline pressure of 500 mTorr, the specific conductance of forelines with diameters 40 mm and 100 mm change drastically from 250 lm/s to 9000 lm/s, respectively. This means the conductance of a foreline with 1 m length and 40 mm diameter is 250 l/s, and the conductance of a foreline with 1 m length and 100 mm diameter is 9000 l/s. The conductance of a foreline with 10 m length and 40 mm diameter is 25 l/s, and the conductance of a foreline with 10 m length and 100 mm diameter is 900 l/s. Therefore, the length and diameter of the foreline has a substantial impact on conductance.

Also, the total pumping conductance loss increases in more than simply an additive function of the conductance loss from the foreline and that from the chamber and valve. For example, Figure 4 shows the total conductance (line 192) in relation to the chamber and valve conductance (line 194) and the foreline conductance (line 196) for increasing flow of gas in a chamber. The total conductance C_T is given by $1/C_T = 1/C_{C/V} + 1/C_F$ where $C_{C/V}$ is the combined chamber and valve conductance, and C_F is the foreline conductance. Thus, the total conductance C_T is always smaller than the chamber/valve conductance $C_{C/V}$ and is always smaller than the foreline conductance C_F and, in fact, is smaller than the smaller of the two. In addition, while the chamber/valve conductance curve **194** is a relatively straight line for increasing gas flow, the foreline conductance curve **196** increases rapidly as the flow rate of the gas is increased. However, since the total conductance **192** is always smaller than both **194** and **196**, even the rapid increase of **196** has a small effect on **192** because **194** has remained relatively constant with increasing gas flows. This is a limiting factor for chambers processing substrates having diameters of 300 mm and higher. Figure 4 also shows that for gas flows up to 4000 sccm, which cover the majority of semiconductor processes, the foreline conductance is the dominating conductance and has the major effect in lowering the

total conductance. Thus, the foreline conductance plays a critical role, and increasing it by using a shorter foreline has a substantial effect on increasing total conductance.

The long forelines result in large losses of pump capacity because of their low conductance. Table I shows calculated foreline losses which are the losses in pump capacity or pumping speed that arise because of the length of the foreline between the pump and chamber, as a function of the length and diameter of the foreline. For example, for a foreline having a constant length of 20 meters, the foreline losses increase from 37% to 65% – as the foreline diameter decreases from 100 to 40 mm. Similarly, for a foreline having a constant diameter of 40 mm, the foreline losses increase from 48% to 65%–as the length of the foreline increases from 10 to 20 m. Thus, the shorter the length of the foreline, the higher the conductance of the foreline and the lower are the pumping losses of the pumping system **155**.

The integrated pumping system **155** illustrated in Figure 2 operates far more efficiently than the remote pumping system **35** illustrated in Figure 1, because of the absence of low conductance pipelines, forelines, and valves and also because much smaller capacity pumps can be substituted for the larger capacity remote pumps that are used in conventional apparatus **15**. For example, Figure 5 shows the required pump capacity (or pumping speed) as a function of process gas flow rate for a remotely located pump, a closely located pump with a short foreline, and an abutting pump. Line 202 shows the pumping speed of a conventional remote pump with a long 50-foot foreline **65a-c**, and that is located in remote environment from a processing apparatus **15**, for example, as shown in Figure 1. Line 204 shows the pumping speed of a pump **165a,b** having a short foreline **190a,b** which demonstrates a substantial increase in pumping efficiency, as shown in Figure 2. Line 206 shows the even higher efficiency of a local abutting pump **165c** having no foreline, also as shown in Figure 2. The difference in height between lines 202 and 206 represents the increase in pump capacity arising from the higher conductance between the pump and the chamber. Thus, foreline losses that accounted for 60 to 80% of the total conductance losses were eliminated by the present pumping system **155**.

TABLE I

FORELINE						VACUUM PUMP		FORELINE
Pipe Length	Pipe Diameter	Pipe Diameter	Specific Conductance	Conductance	Conductance	Pump Speed	Effective Speed	Piping Losses
(m)	(in)	(mm)	(lm/s)	(l/s)	(m^3/hr)	(m^3/hr)	(m^3/hr)	(%)
20	1.5	40	300	15	54	100	35	65
20	2	50	750	38	135	100	57	43
20	2	50	750	38	135	250	88	65
20	3	80	3000	150	540	250	171	32
20	3	80	3000	150	540	500	260	48
20	3	80	3000	150	540	1000	351	65
20	4	100	9500	475	1710	1000	631	37
10	1.5	40	300	30	108	100	52	48
10	2	50	750	75	270	100	73	27
10	2	50	750	75	270	250	130	48
10	3	80	3000	300	1080	250	203	19
10	3	80	3000	300	1080	500	342	32
10	3	80	3000	300	1080	1000	519	48
10	4	100	9500	950	3420	1000	774	23

As a result of reducing the length of the foreline **190a,b**, it is also possible to use a foreline having a small diameter. This is because a large diameter foreline has a large surface area that serves as a heat sink upon which condensates are deposited from the process gas flowing in the pipeline. These condensates are dislodged and loosened by vibrations from the pumps **165a-c** and back diffuse into the chambers **120** to contaminate and reduce the yield of the substrate **20**. For example, Figure 6 shows the increasing deposition area provided by the internal surfaces of forelines having increasing diameters of 16 to 100 mm and foreline lengths. For example, a foreline having a diameter of 40 mm and a length of 1 m has a surface area of approximately 0.128 m^2, while a foreline having a diameter of 100 mm and a length of 20 m has a surface area of 6.4 m^2, which is about 50 times larger. The larger area provides a much bigger surface for condensates to be deposited upon from the process gas flowing in the foreline **190a**. Therefore, it is desirable to have a foreline with a diameter of less than about 80 mm, and more preferably less than about 50 mm. These smaller diameters reduce the foreline surface area by a factor of 10 from an average of about 4 m^2 to less than about 0.4 m^2.

Figure 7 is a graph showing the change in pressure in a chamber as a function of increasing gas flow showing the improved processing window obtained by the integrated pumping system **155** as compared to a remote pumping system **35**. Line 208 is the pressure versus gas flow curve for a remote set of pumps comprising a 80 m^3/hr pre-vacuum pump and a 500 m^3/hr low vacuum pump. Line 212 is the curve for an integrated pumping system **155** comprising a single 100 m^3/hr pre-vacuum pump. Both pumping systems **35**, **155** used a 2000 l/s turbo molecular high vacuum pump **160**. The integrated pumping system **155** had two advantages over the remote pumping system **35**. First, the dual pumps having capacities of 80/500 were replaced by a single pump having a capacity of 100 m^3/hr. In addition, the pump with the large capacity of 500 m^3/hr, which used a lot of energy, was expensive and had a large footprint, was eliminated by the much smaller capacity pump of 100 m^3/hr. Also, the integrated pumping system **155** obtained wider process window in the flow range of 200 to 400 sccm, which is a commonly used flow range for many processes with lower pressures of 6 to 10 mTorr.

In a preferred embodiment, a pre-vacuum pump **165c** is connected directly to a chamber **110** without any length of foreline at all. Eliminating the foreline provides increased pump capacity and reduced contamination from the forelines and valves. This embodiment is especially useful for load-lock chambers **110** that often require rapid cycling between atmospheric pressure and low vacuum pressures of 100 to 300 mTorr. To allow the inlet **170c** of the pump **165c** to be connected adjacent or abutting the chamber **110**, the pump **165c** should have a low-level of vibrations during operation, a relatively small size, and not be excessively noisy. By low level of vibration it is meant a vibrational level of less than about 2.5 m/s^2, and more preferably less than about 1.5 m/s^2. This is achieved by a low vibration pump design and rotational speeds of less than 10,000 rpm, and more preferably less than 7,000 rpm. The small size of the pump **165c** is typically less than about 65 liters, and more preferably less than about 40 liters. These small pump sizes are achieved by higher rotational speed, optimal pumping stages, and motor design. In addition, the pump **165c** should not be excessively noisy to allow operation within the clean or grey room. A sufficiently low noise level is below 65 dB, and more preferably less than about 55 dB. This is achieved by reducing mechanical vibrations and gas compression noises.

The pre-vacuum pumps **165a-c** can be a roots, screw, hook and claw, tongue and groove, or similar principle. Preferably, the pre-vacuum pump **165a** is a screw, roots, hook and claw, or tongue and groove pump that comprises one or more evacuating members that rotate to evacuate gas from a chamber. For example, Figure 8a shows a schematic of a screw pump having a plurality of screw augers that have interlacing blades. The size of the screw augers and the speed of the shaft controls the pump capacity or speed which is a rate of which the pump evacuates gas from a chamber. Figure 8b shows a schematic of a roots-type pump which has two or more rotors also with interdigited blades. In another embodiment, as shown in Figure 8c, the pump comprises a plurality of parallel shafts, each having a hook and claw mechanism that interact with one another to evacuate gas from the chamber. In yet another embodiment, shown in Figure 8d, the pump comprises a rotating member comprising a tongue and groove mechanism on a plurality of shafts. Combinations of these pump mechanisms are also possible.

Preferably, the pressure of the gas in one or all of the chambers is controlled by an open or a closed loop pressure controller **220** that adjusts a speed of the pump to change the pressure of gas in a chamber. For example, Figure 2 shows a pressure controller **220** comprising at least one pressure gauge **225** connected to the chamber **120** for providing a pressure signal P_S in relation to the pressure of the gas in the chamber **120**. The analog or digital pressure signal P_S is transmitted to a pump controller **230**, such as a P, PI, or PID or similar controller and/or a computer system **235**, that compares the signal P_S to a target pressure P_T, and changes the speed of a motor **240** of the pump **165a** in relation to the difference ΔP between the measured and target pressures. A set of rules, such as proportional-integral-derivative rules, are used to adjust the speed or the pump **165a** in proportion to ΔP. As ΔP becomes larger, the increase in pump speed is set to be correspondingly higher, as ΔP is reduced, the pump speed is set to be correspondingly lowered. In addition, the internal and exhaust pressures of the pump **165a** can also be measured using additional gauges and sensors (not shown). The pump controller **230** can be a single controller or a set of controllers that cooperate to perform the pressure measurement, comparison of measured and set-point pressures, and adjustment of the pump speed.

Preferably, the pump controller **230** changes a rotational speed of the pump **165a**. The rotational speed of the pump controls the pump capacity which is the rate of which the pump evacuates a volume of gas from the chamber. Preferably, the pre-vacuum pump **165a** has a low rotational speed that is less than about 10,000 rpm, and more preferably less than about 7,000 rpm. The low rpm is advantageous because it reduces the vibration of the pump during use and reduces power consumption and response time during speeding up and down for pressure control.

In another aspect of the present invention, a variable speed pump is operated by a programmable speed controller (now shown) to closely match an optimal complex-shaped curve of pressure reduction versus time in a chamber. The modeled pressure reduction versus time curve for a chamber is used to rapidly reduce the pressure of gas in the chamber and avoid ice condensation. The complex-shaped smooth curve cannot be closely matched by the step changes in opening size of a two-stage or conventional soft-start valve. In contrast, by adjusting the rotational

speed of the pump through a predetermined range of speeds that can be continuously varied through an entire range of rpm, it is possible to closely trace and match the optimal pressure/time curve.

Figure 9 shows the pressure reduction curves obtained for different configurations of remote and the integrated pumping systems **35**, **155**. In these examples, pre-vacuum pumps **165a-c** were positioned in both remote and integrated positions to compare the reduction in pump-down time achieved by the integrated pumps. Both sets of pumps were operated to evacuate a load-lock chamber. The pumps had different pumping capacities and were operated at different rotational speeds to optimize their pump-down process cycle. Referring to Figure 9, line 272, shows pump-down pressure/time cycles for a remote pump, which has a pump-down time of about 135 seconds. In contrast, lines 284 to 294 are pump-down pressure/time cycles of integrated pumps that were positioned abutting the platform and chambers and with a short foreline having a length of 2 m and a diameter of 50 mm. The local pumps had an average pump-down speed of about 65 seconds, which is twice as fast as the remote pumps.

In these examples, a soft-start valve or a two-step speed adjustment was used in the foreline **76** to control the rate of pressure reduction in the chamber. Some of the pumps used soft-start valves having two opening sizes comprising a small opening size that was initially opened to bring the chamber down from atmospheric pressure to a pressure of 200-300 Torr, and a large opening used to reduce the chamber pressure down to about 0.1 Torr. The change in slopes of the pump down cycles was obtained by either changing from the small to the large valve in the case of the remote pumps, or from one rotational speed to another in the case of the variable speed integrated pumps. For example, the rotational speeds of the pumps were set at one or more of 20, 30, 40, 45, 60, 80, and 100 Hz. Pairs of rotational speeds were used for each integrated pump, including a lower speed and a higher speed, to achieve optimal fast and soft pump down. It is seen that an optimal pump-down cycle was obtained for an integrated pump having a capacity of 100 m^3/hr operated at rotational speeds of 40/100 Hz, **290**, **294**.

Figure 10 shows a computer-generated model of a pressure reduction curve for a process chamber that can be used to rapidly reduce the pressure of gas in the chamber without ice condensation. The computer simulation model was generated for a chamber having a volume of about 6 liters. The rotational speed of an integrated pump mounted on a process chamber was varied through a selected set of increasing speeds to closely match the pressure reduction curve. The set of pump speeds were selected to closely trace the pump capacity or speed to the maximum allowable capacity denoted by the modeled pressure reduction curve, as shown by line 300. In Figure 10, line 302 shows the measured pressure reduction curve obtained in the chamber, when the pump was run at 30 m^3/hr during the initial pressure reduction from atmospheric pressure to 200 Torr, and thereafter, run at 90 m^3/hr for pressure reduction down to 0.1 Torr. Line 302 took the longest time of about 13 seconds to reach 0.1 Torr without ice condensation in the chamber and did not closely match the pressure reduction curve. Line 304 shows the reduction in pressure obtained in the chamber, when the pump was first run at 27 m^3/hr during the initial pressure reduction from atmospheric pressure to 200 Torr, and thereafter, run at 90 m^3/hr for pressure reduction down to 0.1 Torr. This followed more closely the modeled ice condensation curve and took a shorter time of 11 seconds to reach 0.1 Torr without ice condensation providing an improvement in pump down time of about 2 seconds. Line 306 shows optimal results in which the pump was operated through a set of speeds of 8, 27, 90, and 250 m^3/hr, which more closely followed the modeled pressure reduction curve and reduced pump down time from atmospheric pressure to 0.1 Torr in less than about 9 seconds without ice condensation. Thus, a series of continuous or step changes in the effective or rotational speed of the pump provides an optimal pump down cycle that avoids ice condensation in the chamber. The number of step changes depends on the shape of the modeled ice condensation curve, pump capacity, and the volume of the chamber.

The reduction in pump down time is particularly important for the load-lock chamber **110** which is often pumped down from atmospheric pressure to low vacuum pressures. The load-lock chamber **110** is pumped down every time a new batch of substrates is inserted into the load-lock or a processed batch of substrates is removed from the load-lock chamber. Thus, the load-lock chamber **110** is often cycled between atmospheric pressure (during loading and unloading of

substrates) and low pressures during processing or transferring of the substrates **20** from the load-lock chamber **110** to a process chamber **120**. The large number of pump-down cycles, relative to the process chamber **120** which remains at low pressures throughout processing, require fast pump down cycles from atmospheric to low pressure levels of less than about 0.1 Torr.

The pumping system **155** of the present invention also provides considerable energy conservation over conventional pumping systems **35**. The variable speed, integrated, pre-vacuum pump **165a-c** can also be operated more efficiently by reducing the high speed maintained during the operational mode to a low speed or power saving idle mode. Figure 11 is a graph of the electrical power used by the pumping system **155** versus time showing the energy savings obtained during pump-down of a load-lock chamber **110**. Initially, from 0 about 18 seconds, the pre-vacuum pump is operated at a relatively low speed of about 30 Hz from atmospheric pressure down to about 200 Torr – during which time the pump uses a relatively small amount of energy of 500 to 750 watts. Thereafter, the pump speed is accelerated from 30 to 100 Hz over a period of 1 to 2 seconds to achieve a vacuum of about 0.1 Torr in the chamber – the peak energy used during this time is about 3000 watts. Once a low pressure equilibrium state of vacuum is obtained in the chamber, even though the pump continues to operate at 100 Hz, a much smaller amount of energy of about 1500 watts can be used to maintain the load-lock chamber at a low pressure. When the load-lock chamber does not contain substrates, the pump is operated in a power saving idle mode at about 30 Hz to use a very small amount of energy of about 500 watts. Conventional pumps operate at a continuous maximum speed of 50 Hz and 60 Hz, depending on the country network frequency, and use from 3,000 to 8,000 watts. In contrast, the variable speed pump operates at a much lower average energy level of about 500 to 1500 watts, thereby consuming about 6 times less energy than conventional pumps.

In another aspect of the present invention, as shown in Figures 12a and 12b, the pre-vacuum pump **325** comprises a plurality of inlet ports **330a,b**, each connected to an inlet stage **380a,b** of the pump **325**. In prior art systems, as schematically shown in Figure 13, each pump **355a,b** had one inlet port **360a,b** in a single inlet stage **362a,b**, respectively. The inlet ports **360a,b** were each connected

to a separate chamber **350a,b** on the platform **352**. The use of multiple pumps **355a,b** for a single platform **352** resulted in higher capital outlays and increased costs of maintenance of the multiple pumping systems and pipelines, especially when the pumps **355a,b** were located at a distant or remote location from the platform **352**.

In contrast, as schematically shown in Figure 12b, a multiple inlet pump **325** according to the present invention, comprises multiple inlet ports **330a,b**, each of which are connected to a chamber **355a,b** (or a pump) to evacuate the gas in that chamber or pump. Thus, a single pump **325** can perform the work of a multiple set of prior art pumps **355a,b**. When the platform **340** comprises a plurality of chambers **335a,b** mounted contiguously to one another, a single multiple inlet stage pump **325** is used to pump down one or more of the chambers **325a,b**, and thereby increase pumping efficiency, reduce capital costs by eliminating a number of pumps, and save valuable space in the clean room.

The multiple inlet pump **325** comprises a first inlet **330a** connected to a first chamber **335a** or high vacuum pump (not shown) and a second inlet **330b** connected to a second chamber **335b** or another high vacuum pump (not shown). For example, the first inlet **330a** can be connected to a process chamber, and the second inlet **330b** connected to the load-lock or transfer chamber, or both the first and second inlets **330a,b** can be connected to separate process chambers. The multiple inlet pump **325** has a vacuum capacity that is capable of evacuating the plurality of chambers from a pressure of one atmosphere down to a pressure of about 0.1 Torr.

The multiple inlet pump **325** comprises one or more rotatable shafts **370a,b** in separate gas evacuating stages **380-384**. Each stage **380-384** comprises one or more shafts **370a,b** having a plurality of interdigited stages or lobes **385** that interlace each other to form the gas evacuating means within that stage. The low-pressure end **380a,b** of the pump **325** comprises a plurality of inlet ports **330a,b**, each of which are connected to a single chamber **335a,b**, respectively. The first and second inlet ports **330a,b** can be on a single manifold that terminates to a single inlet stage (not shown) or they can be connected to separate inlet stages **380a,b** (as shown). Preferably, the inlet ports **380a,b** terminate at one or more separate inlet

stages **380a,b** that are connected in a parallel arrangement, by which it is meant that the outlets of these two stages do not feed into one another, but instead are combined to feed directly to a second stage **381**. Thereafter, the second stage **381** feeds to the third stage **382**, the third stage **382** feeds to the fourth stage **383**, and the fourth stage **383** feeds to the fifth stage **384**, all in series arrangement. The fifth stage **384** comprises a high pressure exhaust outlet **390** that exhausts the evacuated gas to atmosphere. The plurality of stages **380-384** in a series arrangement serve to increase the pumping efficiency or total pressure reduction achievable by the pump. For example, if each of the first, second, third, fourth, and fifth stages has a compression ratio of about 2, a total of five stages in series arrangement will provide a total compression ration of 2^5 which is about 1000, and the pump can pump down from atmospheric pressure (about 760 Torr) to a thousand times lower or less than about 1 mTorr. Typically each stage of the pump has a compression ratio of from about 2 to about 20.

The multiple inlet pump **325** provides significant cost savings by reducing the total number of pumps, valves, and pressure control systems, that are used on a multi-chamber platform **340**. In addition, the footprint of the apparatus **115** is substantially reduced by use of a single pump to perform the task of multiple pumps. Also, the pumping efficiency is increased by reducing the total length of foreline piping and other pipeline obstructions, such as valves **500**, which only increase losses. As a result, a pump **325** having a relatively low capacity can be used to evacuate more than one chamber, efficiently, and with good pressure control.

While the present invention has been described in considerable detail with reference to certain preferred versions, many other versions should be apparent to those of ordinary skill in the art. For example, the pre-vacuum pump can comprise a non-rotating mechanism that operates in an equivalent manner to a rotating mechanism, and the chambers can be used to process substrates other than semiconductor wafers. Thus, the apparatus, chamber, pumping system **155**, and methods according to the present invention should not be limited to the illustrative embodiments of the invention described herein. Therefore, the spirit and scope of the appended claims should not be limited to the description of the preferred versions contained herein.

What is claimed is:

1. An apparatus for processing a substrate, the apparatus comprising:

(a) a chamber; and

(b) a pump adjacent to the chamber, the pump having an inlet connected to the chamber for evacuating gas in the chamber and an outlet that exhausts the evacuated gas to atmospheric pressure.

2. An apparatus according to claim 1 further comprising a foreline extending between the inlet of the pump and the chamber, the foreline having a length of less than about 2 m.

3. An apparatus according to claim 2 wherein the foreline comprises a diameter of less than about 80 mm.

4. An apparatus according to claim 1 that is substantially absent a foreline between the inlet of the pump and the chamber.

5. An apparatus according to claim 1 wherein the pump is abutting the chamber.

6. An apparatus according to claim 1 wherein the pump comprises a pre-vacuum pump or a low vacuum pump.

7. An apparatus according to claim 1 further comprising a pressure controller for controlling the pressure of the gas in the chamber by adjusting a speed of the pump.

8. An apparatus according to claim 1 wherein the chamber comprises a load-lock chamber, transfer chamber or process chamber.

9. An apparatus for processing a substrate, the apparatus comprising:

(a) a load-lock chamber comprising an enclosure; and

(b) a pump adjacent the load-lock chamber, the pump having an inlet connected to the load-lock chamber for evacuating gas from the load-lock chamber and an outlet that exhausts the gas to atmospheric pressure.

10. An apparatus according to claim 9 wherein the inlet is connected directly to the load-lock chamber and is substantially absent a foreline.

11. An apparatus according to claim 9 further comprising a foreline extending between the inlet of the pump and the load-lock chamber, the foreline having a length of less than about 2 m.

12. An apparatus according to claim 11 wherein the foreline comprises a diameter of less than about 80 mm.

13. An apparatus according to claim 1 wherein the pump is abutting the load-lock chamber.

14. An apparatus according to claim 9 wherein the pump comprises a pre–vacuum pump or a low vacuum pump.

15. An apparatus according to claim 9 further comprising a pressure controller for controlling the pressure of the gas in the load-lock chamber by adjusting a speed of the pump.

16. An apparatus for processing a substrate, the apparatus comprising:

(a) a process chamber comprising a support and a gas distributor; and

(b) a pumping system comprising a pre-vacuum pump adjacent to the process chamber, the pre-vacuum pump having an inlet connected to the

process chamber to evacuate gas from the process chamber and an outlet that exhausts the evacuated process gas to atmospheric pressure,

whereby a substrate held on the support is processed by process gas introduced through the gas distributor into the process chamber.

17. An apparatus according to claim 16 further comprising a high vacuum pump having an inlet connected to the process chamber and an outlet that exhausts to the pre-vacuum pump.

18. An apparatus according to claim 17 wherein the pre-vacuum pump is capable of evacuating the process chamber from about atmospheric pressure to less than about 0.1 Torr, and the high vacuum pump is capable of evacuating the process chamber from about 0.1 Torr to less than about 10^{-9} Torr.

19. An apparatus according to claim 16 further comprising a foreline extending between the inlet of the pre-vacuum pump and the process chamber, the foreline having a length of less than about 2 m.

20. An apparatus according to claim 19 wherein the foreline comprises a diameter of less than about 80 mm.

21. An apparatus according to claim 16 wherein the inlet is connected directly to the process chamber substantially without a foreline.

22. An apparatus according to claim 16 wherein the pre-vacuum pump is abutting the process chamber.

23. An apparatus according to claim 16 further comprising a pressure controller for controlling the pressure of the process gas in the process chamber by adjusting a speed of the pre-vacuum pump.

24. An apparatus for processing a substrate, the apparatus comprising a chamber, a pump, and a pressure controller for controlling a gas pressure in the chamber by providing a signal in relation to the gas pressure to a pump controller that changes the speed of the pump in relation to the signal.

25. An apparatus according to claim 24 wherein the pump controller changes a rotational speed of the pump.

26. An apparatus according to claim 24 wherein the pump controller changes a speed of an evacuating member of the pump.

27. An apparatus according to claim 24 wherein the pump comprises a pre-vacuum pump or a low vacuum pump.

28. An apparatus according to claim 24 that is substantially absent a foreline between the pump and the chamber.

29. An apparatus according to claim 24 wherein a foreline extending between the pump and the chamber comprises a length of less than about 2 m.

30. An apparatus according to claim 24 wherein the pump is abutting the chamber.

31. A method of processing a substrate, the method comprising the steps of evacuating gas from a chamber by a pump and regulating the pressure of the gas in the chamber by adjusting a speed of the pump.

32. The method of claim 31 further comprising the step of placing one or more substrates in a chamber comprising a load-lock, transfer or process chamber.

33. The method of claim 31 comprising the step of adjusting a rotational speed of an evacuating member of the pump.

34. The method of claim 31 further comprising the step of measuring a pressure of gas in the chamber and adjusting the speed of the pump in relation to the measured pressure of gas.

35. A method of processing a substrate in a chamber, the method comprising the steps of:

(a) placing a substrate on a support in the chamber and evacuating the chamber with a pump;

(b) introducing gas into the chamber, and optionally energizing the process gas, to process the substrate on the support; and

(c) regulating the pressure of the gas in the chamber by adjusting a speed of the pump.

36. The method of claim 35 wherein step (c) comprises the step of adjusting a rotational speed of the pump.

37. The method of claim 35 wherein step (c) further comprises the step of measuring a pressure of the gas in the chamber and adjusting a speed of the pump in relation to the measured pressure of gas in the chamber.

38. An apparatus for processing a substrate, the apparatus comprising a pump having a plurality of inlet ports, a first inlet port provided to evacuate gas from a first chamber or first pump, and a second inlet port provided to evacuate gas from a second chamber or second pump.

39. An apparatus according to claim 38 wherein the first inlet port is connected to the first chamber and the second inlet port is connected to the second chamber.

40. An apparatus according to claim 38 wherein the first and second inlet ports are connected to one or more inlet stages of the pump.

41. An apparatus according to claim 38 wherein the inlet stages are connected to other stages of the pump in a parallel arrangement.

42. An apparatus according to claim 38 wherein the pump abuts at least one of the chambers.

43. An apparatus according to claim 38 wherein the pump comprises an outlet that exhausts the evacuated gas to atmospheric pressure.

44. An apparatus according to claim 38 further comprising forelines that extend between the inlets ports and the chambers or other pumps, the forelines each having a length of less than about 2 m.

45. An apparatus according to claim 38 wherein the inlet ports are connected directly to the chambers or other pumps substantially without forelines.

46. An apparatus according to claim 38 wherein the pump comprises a pre-vacuum pump or a low vacuum pump.

47. An apparatus according to claim 38 further comprising a pressure controller for controlling the pressure of gas in the chambers by adjusting a speed of the pump.

48. An apparatus for processing a substrate, the apparatus comprising a multiple inlet pump having a first inlet port in a first inlet stage, and a second inlet port in a second inlet stage, the first inlet port provided to evacuate gas from a first chamber or first pump, and a second inlet port provided to evacuate gas from a second chamber or second pump.

49. An apparatus according to claim 48 wherein the first inlet port is connected to the first chamber and the second inlet port is connected to the second chamber.

50. An apparatus according to claim 48 wherein the multiple inlet pump abuts at least one of the chambers.

51. An apparatus according to claim 48 wherein the multiple inlet pump comprises an outlet that exhausts the evacuated gas to atmospheric pressure.

52. An apparatus according to claim 48 further comprising forelines that each have a length of less than about 2 m.

53. An apparatus according to claim 48 wherein the inlet ports are connected directly to the chambers or other pumps substantially without forelines.

54. An apparatus according to claim 48 wherein the multiple inlet pump comprises a pre-vacuum pump or a low vacuum pump.

55. An apparatus according to claim 48 further comprising a pressure controller for controlling the pressure of gas in the chambers by adjusting a speed of the pump.

56. An apparatus for processing a substrate, the apparatus comprising:

(a) a plurality of chambers that are shaped and sized to hold one or more substrates; and

(b) a pump having a first inlet port in a first inlet stage, and a second inlet port in a second inlet stage, the first inlet port provided to evacuate gas from one chamber and a second inlet port provided to evacuate gas from another chamber.

57. An apparatus according to claim 56 wherein the plurality of chambers are mounted on a single platform, and the pump abuts the platform.

58. An apparatus according to claim 56 wherein the first inlet port is connected to a first chamber and the second inlet port is connected to a second chamber.

59. An apparatus according to claim 56 wherein the pump abuts at least one of the chambers.

60. An apparatus according to claim 56 wherein the pump comprises an outlet that exhausts the evacuated gas to atmospheric pressure.

61. An apparatus according to claim 56 further comprising forelines extending between the inlets ports and the chambers, the forelines each having a length of less than about 2 m.

62. An apparatus according to claim 56 wherein the inlet ports are connected directly to the chambers substantially without forelines.

63. An apparatus according to claim 56 wherein the pump comprises a pre-vacuum pump or a low vacuum pump.

64. An apparatus according to claim 56 further comprising a pressure controller for controlling the pressure of gas in the chambers by adjusting a speed of the pump.

ABSTRACT

An apparatus **115** for processing a substrate **20**, comprises an integrated pumping system **155** having a high operating efficiency, small size, and low vibrational and noise levels. The apparatus **115** comprises a chamber, such as a load-lock chamber **110**, transfer chamber **115**, or process chamber **120**. An integrated and local pump **165** is abutting or adjacent to one of the chambers **110, 115, 120** for evacuating gas from the chambers. The pump has an inlet **170** connected to a chamber **110, 115, 120**, and an outlet **175** that exhausts the gas to atmospheric pressure. Preferably, the pump **165** comprises a pre-vacuum pump or a low vacuum pump.

U.S. PENDING PATENT APPLICATION

ATTORNEY DOCKET NO.: 2981/USA/SMO/PJS
SERIAL NO.: N/A - FILED: HEREWITH
INVENTORS: REIMER, ET AL.

EXAMINER'S INITIALS		PENDING U.S. PATENT APPLICATION(S)
	AA	U.S. Patent Application entitled, "An Apparatus and Method for Regulating a pressure in a Chamber," filed ____________; Serial No. ____________; Inventors: Beyers, et al.
	AB	
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	AI	
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APPLICATION FOR UNITED STATES LETTERS PATENT

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INVENTION: AN APPARATUS AND METHOD FOR REGULATING A PRESSURE IN A CHAMBER

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AN APPARATUS AND METHOD FOR REGULATING A PRESSURE IN A CHAMBER

BACKGROUND OF THE INVENTION

The invention relates generally to an apparatus and a method for regulating a pressure in a chamber.

In Fig. 1, a prior art system is shown for generating a vacuum in a chamber, such as that used in the manufacturing or processing of semiconductor products, such as devices and wafers. The chamber 1 has a process gas injected at a flow rate of QHv. The pressure PHv in the chamber 1 is measured with the gauge or sensor 5, which generates the pressure signal P. To generate a high vacuum in the chamber 1, the intake side of a high vacuum pump 2 is coupled to the chamber 1. Typically, a turbo molecular pump is used as the high vacuum pump 2. Further, the intake side of a roots vacuum pump 3, which is a type of rotary blower, is coupled to the exhaust side of the high vacuum pump 2, and the exhaust side of the roots vacuum pump 3 is coupled to the intake side of a pre-vacuum pump 4.

In the prior art system of Fig. 1, the pressure PHv of the chamber 1 is regulated using the throttle valve 8. The pressure signal P corresponds to the pressure PHv of the chamber 1 measured with the gauge or sensor 5. Based on the

pressure signal P, the system operator 6 manually or automatically determines a desired set point pressure for the chamber 1 and generates a set pressure signal Ps corresponding to the desired set point pressure. The set point pressure signal Ps is used by the controller 7 to generate a signal u, which is used to vary the cross-section of the throttle valve 8. In so doing, the pressure PHv of the chamber 1 is regulated, and a high vacuum within chamber 1 is achieved.

SUMMARY OF THE INVENTION

It is an object of the present invention to decrease the dimensions and, specifically, the footprint of the chamber by eliminating the throttle valve of the prior art system.

A further object of the present invention is to increase the conductance, which is mass flow divided by a pressure difference or drop over a distance, of the chamber by eliminating the throttle valve of the prior art system. In this way, a higher pumping speed for the high vacuum pump is obtained, and a smaller and more cost effective high vacuum pump may be used for some applications.

Still a further object of the present invention is to increase the throughput of the system, especially one used of semiconductor manufacturing and processing, by eliminating the throttle valve. Because the throttle valve is a source of impurities and particles in the chamber, the throttle valve

must be cleaned regularly. This requires stopping the production process and opening the chamber to clean the system.

An additional object of the present invention is to increase the overall reliability of the system by eliminating the throttle valve, which is typically an unreliable mechanical part. For a chamber used in the manufacturing and processing of semiconductor products, this increase in reliability is especially desirable.

Another object of the present invention is to decrease the time required to obtain a desired pressure and vacuum in the chamber, and thereby increasing the manufacturing throughput of the chamber. For example, if the chamber is used for manufacturing or processing of semiconductor products, the throughput of the semiconductor products can be improved.

Yet another object of the present invention is to homogenize the flow between the high vacuum pump and the chamber.

Still yet another object of the present invention is to influence insignificantly the composition of the process gas entering the chamber.

The above objects and advantages of the present invention are achieved by an apparatus and a method for regulating a pressure in a chamber. The apparatus for regulating the

pressure in the chamber comprises: a first vacuum pump having a compression stage, an exhaust side, and an intake side communicating directly with the chamber for generating a first pressure in the chamber; a controllable pressure regulator coupled to the first vacuum pump and having a control input for receiving a first signal for regulating an exhaust pressure at the exhaust side of the first vacuum pump or an internal pressure at the compression stage of the first vacuum pump, and to thereby regulate the pressure in the chamber; and a controller having an input for receiving a second signal representing a control pressure in the apparatus, and an output connected to the control input of the controllable pressure regulator, the controller producing at the output the first signal as a function of the second signal.

The method for regulating a pressure in the chamber, wherein a first vacuum pump has a compression stage, an exhaust side, and an intake side communicating directly with the chamber, comprises the steps of: generating a first pressure in the chamber with the first vacuum pump; and controlling an exhaust pressure at the exhaust side of the first vacuum pump or an internal pressure at the compression stage of the first vacuum pump as a function of a control pressure in the apparatus to thereby regulate the pressure in the chamber.

Moreover, the above objects and advantages of the present invention are illustrative, and not exhaustive, of those which can be achieved by the present invention. Thus, these and other objects and advantages of the present invention will be apparent from the description herein or can be learned from practicing the invention, both as embodied herein and as modified in view of any variations which may be apparent to those skilled in the art.

BRIEF DESCRIPTION OF THE INVENTION

Fig. 1 is a function block diagram illustrating the prior art system for generating a vacuum in a chamber.

Fig. 2 is a function block diagram illustrating a first embodiment of the invention.

Fig. 3 is a function block diagram illustrating the controller 9 of Fig. 2.

Fig. 4 compares the compression characteristics of the prior art system and the first embodiment of the present invention.

Fig. 5 is a function block diagram illustrating a second embodiment of the invention.

Fig. 6 is a function block diagram illustrating the controller 12 of Fig. 5.

Fig. 7 is a function block diagram illustrating a third embodiment of the invention.

Fig. 8 is a function block diagram illustrating a fourth embodiment of the invention.

Fig. 9 is a function block diagram illustrating a fifth embodiment of the invention.

Fig. 10 is a function block diagram illustrating a sixth embodiment of the invention.

Fig. 11 is a function block diagram illustrating a seventh embodiment of the invention.

Fig. 12 is a function block diagram illustrating a eighth embodiment of the invention.

Fig. 13 is a function block diagram illustrating a ninth embodiment of the invention.

Fig. 14 is a function block diagram illustrating a tenth embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to the accompanying drawings, wherein similar referenced characters refer to similar referenced parts throughout the drawings, Figs. 2-14 depict an apparatus and a method of a first through tenth embodiments of the present invention for generating a vacuum in a chamber and regulating the pressure therein.

FIRST EMBODIMENT

Instead of controlling the pressure PHv in the chamber 1 with a throttle valve 8 as in the prior art system of Fig. 1, the first embodiment of the present invention as shown in Figs. 2-3 controls the rotational velocity of the roots vacuum pump 3, which thereby changes the exhaust pressure of the high vacuum pump 2 and hence the chamber's pressure PHv.

In the preferred embodiment, the high vacuum pump 2 is a turbo molecular pump, which has several pumping or compressing stages, each of which successively compresses the gases of the chamber 1 from 10^{-6} to 10^{-7} Torr (intake pressure) to 1.0 to 2.0 Torr (exhaust pressure). Of the turbo molecular pumps available for use as the high vacuum pump 2, the preferable turbo molecular pump is a MAG 2000 turbo molecular pump manufactured by Leybold Vacuum GmbH of Köln, Germany, which is able to compress exhaust pressures of 1.0 to 2.0 Torr to intake pressures of 10^{-6} to 10^{-7} Torr. Alternatively, any turbo molecular pump can be used that is able to produce low intake pressures suitable for the process in the chamber. As another alternative, any pump can be used that is able to produce low intake pressures suitable for the process in the chamber.

In the preferred embodiment, the roots vacuum pump 3 is the Roots Blower WS 251 PFPE manufactured by Leybold Vacuum GmbH of Köln, Germany, which has a compression ratio in the

range of 3 to 5. Alternatively, any pump, such as a roots vacuum pump or a rotary pump, can be used that is able to adjust the exhaust pressure of the high vacuum pump 2.

In the preferred embodiment, the pre-vacuum pump 4 is the DRYVAC D100 pump manufactured by Leybold Vacuum GmbH of Köln, Germany, which is capable of compressing exhaust pressures at atmosphere to intake pressures of 0.01 to 1.0 Torr. Alternatively, any pump, such as a roughing pump or a rotary pump, can be used that has a minimum intake pressure approximately greater than the maximum exhaust pressure of the high vacuum pump 2.

In all the preferred embodiments of the invention, the chamber 1 is used for the manufacturing or processing of semiconductor products, such as devices and wafers, using semiconductor manufacturing or processing equipment, such as that used for etch, chemical vapor deposition ("CVD"), physical vapor deposition ("PVD"), thin film technology ("TFT"), and ion implantation. In the preferred embodiment, the pressure in the chamber 1 needs to be regulated around 0.1 to 0.001 Torr for use in the manufacturing or processing of semiconductor products.

Alternatively, the chamber 1 may be that used in any application which requires regulating the pressure in the chamber 1 at a constant pressure.

The system operator 6 determines a desired set point pressure for the chamber 1 based on the pressure signal P from the gauge or sensor 5, which measures the pressure PHv of the chamber 1. The determination of the desired set point pressure can be performed manually or automatically. The system operator 6 generates the set point pressure signal Ps based on the desired set point pressure.

In the preferred embodiment, the pressure signal P and the set point pressure signal Ps are voltage signals between 0 and 10 volts. Alternatively, the pressure signal P and the set point pressure signal Ps can be any other analog signals or digital signals.

The controller 9 uses the pressure signal P and the set point pressure signal Ps to determine a frequency signal f. The frequency signal f1 is used to control the rotational frequency of the roots vacuum pump 3. In the preferred embodiment, the rotational frequency of the roots vacuum pump 3 is varied between 10 and 100 Hz using the frequency signal f1. By changing the rotational frequency of the roots vacuum pump 3, the exhaust pressure of the high vacuum pump 2 is changed. The chamber pressure PHv is also changed. Thus, by regulating the rotational frequency of the roots blower, the pressure in chamber 1 is regulated.

The intake pressure of the high vacuum pump 2 is a function of the flow rate QHv and the compression ratio of the

high vacuum pump 2, which is determined by the structural design of the high vacuum pump 2. The effective compression ratio of the high vacuum pump 2 is the ratio of the final pressure-corrected exhaust pressure of the high vacuum pump 2 to the final pressure-corrected intake pressure of the high vacuum pump 2. At a constant flow rate QHv, a typical compression characteristic for the high vacuum pump 2, which is dependent on the design of the high vacuum pump 2, has a maximum at a certain exhaust pressure for the high vacuum pump 2.

At a constant flow rate QHv, the exhaust pressure of the high vacuum pump 2 is dependent on the pumping speed of the pre-vacuum pump 4, the conductance between the intake side of the pre-vacuum pump 4 and the exhaust side of the high vacuum pump 2, and the change in pressure due to varying the rotational frequency of the roots vacuum pump 2. In the preferred embodiment, the minimum exhaust pressure of the high vacuum pump 2 is attained at the maximum pumping speed of the pre-vacuum pump 4.

To generate a low pressure in the chamber 1 at a constant QHv, the intake pressure of the pre-vacuum pump 4 is first decreased, thereby decreasing the exhaust pressure of the high vacuum pump 2 and the chamber's pressure PHv. Initially, the pre-vacuum pump 4 creates a first pressure less than atmosphere both on the exhaust side of the high vacuum pump 2

and in the chamber 1. Alternatively, the high vacuum pump 2 can be bypassed such that the first pressure is created in the chamber 1 but not on the exhaust side of the high vacuum pump 2.

After this first pressure is created by the pre-vacuum pump 4, the high vacuum pump 2 creates a low pressure less than the first pressure in the chamber 1. If the first pressure is created both on the exhaust side of the high vacuum pump 2 and in the chamber 1, the creating of the low pressure in the chamber 1 occurs slowly. Alternatively, if the first pressure is created in the chamber 1 but not on the exhaust side of the high vacuum pump 2, the creating of the low pressure in the chamber 1 occurs rapidly.

In the preferred embodiment, the relationship between the pressures of the exhaust and intake sides of the high vacuum pump 2 is designed to be as continuous and linear as possible to enable use of commercially available controllers.

In the preferred embodiment, the controller 9 selects the frequency signal f1 according to a proportional-integral-derivative ("PID") control rule. As shown in Fig. 3, the controller 9 uses the PID control rule 20, which has as its inputs the pressure signal P and the set point pressure signal Ps and as its output the frequency signal f. The PID control rule 20 is given by the following:

$$f(t) = Kp(P(t)-Ps(t)) + Ki\int^{t}(P(x)-Ps(x))dx + Kd(d(P(t)-Ps(t))/dt) \quad (1)$$

where Kp is the proportional gain, Ki is the integral gain, Kd is the derivative gain, f, P, and Ps are functions of time t, and x is the variable of integration. The PID control rule 20 can be implemented in either discrete or continuous form, and the controller 9 can be either a digital or an analog controller. Alternatively, other control rules may be used instead of the PID control rule 20.

In the preferred embodiment, the PID gains are selected using a gain scheduler 21. The gain scheduler 21 selects the three PID gains Kp, Ki, and Kd based on the set point pressure signal Ps. In the preferred embodiment, the range of the set point pressure signal Ps is divided into eight regions. As the set point pressure signal Ps varies amongst these eight regions, the gain scheduler 21 supplies the PID control rule 20 with the three PID gains associated with the region where the set point pressure signal Ps lies.

As an example, if the gain scheduler 21 has three regions, the three PID gains are determined as follows:

$$
\begin{array}{lll}
Kp=Kp1,\ Ki=Ki1,\ Kd=Kd1 & \text{if } Ps < th1 & \\
Kp=Kp2,\ Ki=Ki2,\ Kd=Kd2 & \text{if } th1 \le Ps < th2 & (2) \\
Kp=Kp3,\ Ki=Ki3,\ Kd=Kd3 & \text{if } Ps \ge th2 &
\end{array}
$$

where Kp1, Kp2, and Kp3 are the three proportional gains for the three regions, Ki1, Ki2, and Ki3 are the three integral gains for the three regions, Kd1, Kd2, and Kd3 are the three derivative gains for the three regions, and th1 and th2 are the thresholds for separating the three regions of the set point pressure signal Ps. The gain scheduling by the gain scheduler 21 can be implemented in either discrete or continuous form, and the gain scheduler 21 can be either a digital or analog gain scheduler.

With the three PID gains from the gain scheduler 21, the pressure signal P, and the set point pressure signal Ps, the PID control rule 20 determines the frequency signal f according to equation (1).

In the preferred embodiment, the derivative gain Kd is set to zero (0) for the entire range of the set point pressure signal Ps. In other words, in the preferred embodiment, the PID control rule reduces to a proportional-integral ("PI") control rule. Alteratively, any combination of the three PID gains can be set to zero (0) as long as at least one is non-zero.

As an alternative to using the gain scheduler 21, a single set of PID gains can be used for the entire range of the set point pressure signal Ps. As another alternative, any signal relevant to the control of the system can be used as the input to the gain scheduler 21 to select the gains for the control rule. As a further alternative, any combination of signals relevant to the control of the system can be used as the input to the gain scheduler 21 to select the gains for the control rule.

To ease the transition between the PID gains selected by the gain scheduler 21, interpolation between the immediately selected set of PID gains and the previously selected set of PID gains can be used. For example, a linear interpolation between these two sets can be employed.

In addition to or instead of controlling the rotational frequency of the roots vacuum pump 3, the exhaust pressure of the high vacuum pump 2 can be changed using the controller 10 and the control valve 11. By injecting gas into the conduit between the roots vacuum pump 3 and the high vacuum pump 2, the exhaust pressure of the high vacuum pump 2 can be changed. By increasing or decreasing the injection of gas into the conduit between the roots vacuum pump 3 and the high vacuum pump 2, the exhaust pressure of the high vacuum pump 2 can be increased or decreased, respectively. In this way, the

exhaust pressure of the high vacuum pump 2 is regulated, and hence the pressure of the chamber 1 is regulated.

To regulate the exhaust pressure of the high vacuum pump 2, the control valve 11 controls the amount of gas injected into the conduit, and the controller 10 determines the extent to which the control valve 11 is opened or closed.

In the preferred embodiment, the controller 10 controls the extent to which the control valve 11 is opened or closed according to the following:

$$\begin{aligned} u1&=1 && \text{if } Ps < th3 \\ u1&=K1(Ps+K2) && \text{if } th3 \le Ps < th4 \\ u1&=0 && \text{if } Ps \ge th4 \end{aligned} \qquad (3)$$

where u1=1 indicates that the control valve 11 is fully open, u1=0 indicates that the control valve 11 is fully closed, u1 between 0 and 1 indicates that the control valve 11 is partially closed or partially open, K1 and K2 are variables selected such that u1 is between 0 and 1, and th3 and th4 are thresholds for separating regions of the set point pressure signal Ps.

Alternatively, the control valve can be either fully opened or fully closed according to the following control rule:

$$u1=1 \qquad \text{if } Ps < th3 \qquad (4)$$

$$u1=0 \qquad \text{if } Ps \geq th3$$

Alternatively, a PID control rule, as described above, with or without a gain scheduler, as described above, may be used as the control rule for controlling the control valve 11.

EXAMPLE OF THE FIRST EMBODIMENT

In Fig. 4, the characteristic curve for the high vacuum pump 2 of the prior art system as shown in Fig. 1 is compared with the characteristic curve for the high vacuum pump 2 of the first embodiment of the invention as shown in Fig. 2. In Fig. 4, the abscissa is the exhaust pressure for the high vacuum pump 2, and the ordinate is the intake pressure for the high vacuum pump 2. For comparison, the same high vacuum pump is used, namely the MAG 2000 turbo molecular pump manufactured by Leybold Vacuum GmbH of Köln, Germany. The difference between the two is that to regulate the pressure in the chamber 1, the prior art system uses the throttle valve, and the first embodiment uses the rotational frequency controlled roots vacuum pump.

As can be seen in Fig. 4, the first embodiment, indicated by the line with open triangles, is able to achieve a higher intake pressure for a lower exhaust pressure than the prior art system, indicated by the line with solid squares.

Further, the first embodiment achieves a smoother transition between the horizontal and near vertical portions of the characteristic curve than the prior art system. This smoother transition allows for better control of the system by the controller 9.

SECOND EMBODIMENT

In the second embodiment of the present invention, as shown in Figs. 5 and 6, the roots vacuum pump 3 and the control valve 11 of the first embodiment are replaced by a control valve 13. The controller 12 uses the pressure signal P from the sensor 5 and the set point pressure signal Ps from the system operator 6 to determine a control signal u2, which is used to regulate the opening and closing of the control valve 13.

In the preferred embodiment, the control valve 13 should be situated as closely as possible to the high vacuum pump 2 in order to minimize the relevant volume of the conduit between the control valve 13 and the high vacuum pump 2.

In the preferred embodiment, the control valve 13 is opened and closed using a fine resolution stepping motor. Further, for use with semiconductor manufacturing or processing within the chamber 1, the control valve 13 should be tolerable of wide temperature variations.

As shown in Fig. 6, controller 12 uses a PID control rule 22 and a gain scheduler 23, both of which are similar to the PID control rule 20 and gain scheduler 21, respectively, of controller 9. To determine the control signal u2, the PID control rule 22 uses the following:

$$u2(t) = Kp(Ps(t)-P(t)) + Ki\int^{t}(P(x)-Ps(x))dx + Kd(d(P(t)-Ps(t))/dt) \qquad (5)$$

where Kp is the proportional gain, Ki is the integral gain, Kd is the derivative gain, u2, P, and Ps are functions of time t, and x is the variable of integration. The PID control rule 22 can be implemented in either discrete or continuous form, and the controller 12 can be either a digital or an analog controller. Alternatively, other control rules besides the PID control rule can be used by the controller 12.

In the preferred embodiment, the gain scheduler 23, like the gain scheduler 21, selects the three PID gains for the PID control rule 22 based on the set point pressure signal Ps. Alternatively, any signal relevant to the control of the system can be used as the input to the gain scheduler 23.

THIRD EMBODIMENT

In the third, fourth, and fifth embodiments, the high vacuum pump 2 of the first embodiment is a modified turbo molecular pump. These three embodiments are respectively illustrated with function block diagrams in Figs. 7, 8, and 9. For each of the three embodiments, the goal is to decrease the compression ratio for the high vacuum pump 2. For ease of explanation, the graphical symbol for the high vacuum pump 2 in Figs. 2 and 5 is replaced by a more detailed one for the embodiment of a turbo molecular pump in Figs. 7-9.

In some applications, such as in the manufacturing or processing of semiconductor products, such as devices or wafers, various gases are injected into the chamber 1 and have various pressure compressions. For those gases having a higher pressure compression, for example BCl_3 or SF_6, the high vacuum pump 2 will have a larger power consumption than for those gases having a lower pressure compression, for example H_2. To avoid this higher power consumption by the high vacuum pump 2, the compression ratio of the high vacuum pump 2 can be adjusted, and three such ways are described next as the third, fourth, and fifth embodiments.

In the third embodiment as illustrated in Fig. 7, the high vacuum pump 2 is a turbo molecular pump modified by including a bypass from one of the intermediate compression stages in the turbo molecular pump 2 to the exhaust side of

the turbo molecular pump 2. Control valve 31 controls the flow between the bypassed intermediate compression stage and the exhaust side of the turbo molecular pump 2. In this manner, the compression ratio of the turbo molecular pump 2 can be altered.

In the preferred embodiment, control valve 31 is either fully opened or fully closed. Alternatively, the control valve 31 can be partially opened or partially closed.

As an example, with the control valve 31 fully closed, an exhaust pressure of 5 Torr is required to achieve an intake pressure of 20 mTorr for the turbo molecular pump 2. However, with the control valve 31 fully open, an exhaust pressure of 2 Torr is required to achieve an intake pressure of 20 mTorr for the turbo molecular pump 2.

The extent to which the control valve 31 is opened or closed is controlled by the control rule of controller 32. Controller 32 adjusts the control valve 31 according to a control rule based on, for example, the pressure signal P, the set point pressure signal Ps, or any other signal relevant to controlling the system. The control rule used here may be similar to that used by controller 10 to adjust the control valve 11 as in the first embodiment. Alternatively, the control rule may be a PID control rule, as discussed above for the first embodiment, and may include a gain scheduler, as discussed above for the first embodiment. As an alternative,

the control rule may be any control rule useful for controlling the control valve 31.

FOURTH EMBODIMENT

In the fourth embodiment as shown in Fig. 8, the high vacuum pump 2 of the first embodiment is a turbo molecular pump modified by including an injection of gas into one of the intermediate compression stages of the turbo molecular pump 2. The injection of the gas is controlled by the control valve 33, which is controlled by controller 34. As such, the compression ratio of the turbo molecular pump 2 can be increased.

In the preferred embodiment, the control valve 33 is fully opened or fully closed. Alternatively, the control valve 33 can be partially opened or partially closed.

The extent to which the control valve 33 is opened or closed is controlled by the control rule of controller 34. Controller 34 adjusts the control valve 33 according to a control rule based on, for example, the pressure signal P, the set point pressure signal Ps, or any other signal relevant to controlling the system. The control rule used here may be similar to that used by controller 10 to adjust the control valve 11 as in the first embodiment. Alternatively, the control rule may be a PID control rule, as discussed above for the first embodiment, and may include a gain scheduler, as

discussed above for the first embodiment. As an alternative, the control rule may be any control rule useful for controlling the control valve 33.

FIFTH EMBODIMENT

In the fifth embodiment as shown in Fig. 9, the high vacuum pump 2 of the first embodiment is replaced with a turbo molecular pump modified to include several valves for bypassing intermediate compression stages of the turbo molecular pump, and so doing without recirculation. The control valves 35, 36, and 37 are used to disable the compression stages of the turbo molecular pump. A controller 38 is used to adjust the control valves 35, 36, and 37. As is shown in Fig. 9, three control valves are used. Alternatively, any number of control valves up to the number of compression stages of the turbo molecular pump can be used. As such, the compression ratio of the turbo molecular pump 2 can be varied.

In Fig. 9, the exhaust side of the high vacuum pump 2 is shown not coupled to the exhaust sides of control valves 35, 36, and 37. Alternatively, an additional control valve can be added having an intake side coupled to the exhaust side of the high vacuum pump 2 and an exhaust side coupled to the exhaust sides of control valves 35, 36, and 37 and to the intake side of the roots vacuum pump 3. This additional control valve can

be controlled by controller 38 such that gases from the exhaust side of the high vacuum pump 2 are not coupled with gases from the exhaust sides of control valves 35, 36, and 37.

In the preferred embodiment, the control valves 35, 36, and 37 are either fully opened or fully closed. Alternatively, control valves 35, 36, and 37 can be partially opened or partially closed.

The extent to which the control valves 35, 36, and 37 are opened or closed is controlled by the control rule of controller 38. Controller 38 adjusts the control valves 35, 36, and 37 according to a control rule based on, for example, the pressure signal P, the set point pressure signal Ps, or any other signal relevant to controlling the system. The control rule used here may be similar to that used by controller 10 to adjust the control valve 11 as in the first embodiment. Alternatively, the control rule may be a PID control rule, as discussed above for the first embodiment, and may include a gain scheduler, as discussed above for the first embodiment. As an alternative, the control rule may be any control rule useful for controlling the control valves 35, 36, and 37.

As an example, if the turbo molecular pump has 20 compression stages, the three control valves 35, 36, and 37 could be coupled to the fifteenth, tenth, and fifth compression stages, respectively. If the control valve 35 is

opened and the control valves 36 and 37 are closed, compression stages 16 through 20 are bypassed. Moreover, if control valves 35 and 36 are open and control valve 37 is closed, compression stages 11 through 20 are bypassed. In this manner, the compression ratio of the turbo molecular pump 2 is decreased.

SIXTH EMBODIMENT

In the sixth embodiment as shown in Fig. 10, the first, third, fourth, and fifth embodiments are combined. Instead of using multiple controllers, a single controller 42 is used to control all the control valves and pumps. The controller 42 can implement the control rules, as discussed above. Alternatively, the controller 42 can implement a multi-variable control rule. As another alternative, any control rule or control rules useful for controlling the system can be used.

In addition to the bypass control valves in the third, fourth, and fifth embodiments, additional control valves are in the sixth embodiment. The control valve 38 is used to bypass the high vacuum pump 2. The control valve 39 functions as the control valve 31 in Fig. 7 and as discussed in the third embodiment. The control valve 40 is used to implement the bypass of the exhaust of the high vacuum pump 2 as in Fig. 9 and as discussed above in the fifth embodiment. The

combination of control valves 38, 39, and 40 can be used to bypass the high vacuum pump 2 completely. As discussed above in the fifth embodiment, the control valves 35 and 36 are used to bypass the compression stages in the high vacuum pump 2. Alternatively, one or more compression stages can be bypassed using a single control valve with each side of the control valve coupled to a different compression stage.

The control valves 35, 36, 38, 39, and 40 are controlled as described above for the control valves 31, 33, 35, 36, and 37. In practicing the invention, the control valves can be used in any combination to regulate the pressure in the chamber 1. Alternatively, additional control valves can be added to bypass the high vacuum pump 2 or any of its compression stages.

The gauge or sensor 41 measures the pressure PVv at the exhaust of the high vacuum pump 2. Gauge or sensor 41 can produce an analog or digital signal. The signal from gauge or sensor 41 can be used to control the system according to a control rule or control rules in controller 42.

In the preferred embodiment, to regulate the pressure in the chamber 1, the roots vacuum pump 3 is primarily used. Alternatively, any combination of the control valves can be used in addition to or instead of the roots vacuum pump 3 to regulate the pressure in the chamber 1.

SEVENTH EMBODIMENT

In the seventh embodiment as shown in Fig. 11, the roots vacuum pump 3 of the sixth embodiment is replaced by the control valve 13 of the second embodiment. As in the second embodiment, the control valve 13 regulates the exhaust pressure PVv of the high vacuum pump 2 and in turn regulates the pressure PHv of the chamber 1.

In the preferred embodiment, to regulate the pressure in the chamber 1, the control valve 13 is primarily used. Alternatively, any combination of the control valves or additional control valves can be used in addition to or instead of the control valve 13 to regulate the pressure in the chamber 1.

EIGHTH EMBODIMENT

In the eighth embodiment as shown in Fig. 12, the roots vacuum pump 3 of the sixth embodiment is eliminated. In place of regulating the pressure in the chamber 1 by controlling the rotational frequency of the roots vacuum pump 3, the rotational frequency of the pre-vacuum pump 4 is controlled with the frequency signal f2. The controller 42 generates the frequency signal f2 as described above for the generation of the frequency signal f1 by the controller 9. Similar to the embodiments described above, by varying the rotational

frequency of the pre-vacuum pump 4, the exhaust pressure PVv of the high vacuum pump 2 is regulated and, hence, the pressure PHv of the chamber 1 is regulated.

In the preferred embodiment, to regulate the pressure in the chamber 1, the pre-vacuum pump 4 is primarily used. Alternatively, any combination of the control valves or additional control valves can be used in addition to or instead of the pre-vacuum pump 4 to regulate the pressure in the chamber 1.

NINTH EMBODIMENT

In the ninth embodiment as shown in Fig. 13, the roots vacuum pump 3 of the sixth embodiment is eliminated. In place of regulating the pressure in the chamber 1 by controlling the rotational frequency of the roots vacuum pump 3, the pressure in the chamber 1 is regulated by increasing or decreasing the injection of gas via control valve 11, as described above in the first embodiment.

Alternatively, instead of using the control valve 11, the pressure in the chamber 1 can be regulated by increasing or decreasing the injection of gas via control valve 33, as described above in the fourth embodiment.

As another alternative, the combination of using control valves 11 and 33 can be used to regulate the pressure in the chamber 1.

In the preferred embodiment, to regulate the pressure in the chamber 1, a combination of the control valves 1 and 33 is primarily used. Alternatively, any combination of the remaining control valves or additional control valves can be used in addition to or instead of the control valves 1 and 33 to regulate the pressure in the chamber 1.

TENTH EMBODIMENT

In the tenth embodiment as shown in Fig. 14, the roots vacuum pump 3 and the pre-vacuum pump 4 of the sixth embodiment are eliminated, and the high vacuum pump 2 is replaced by a high compression pump 43. The high compression pump 43 compresses gases with an intake pressure of a low value required by the use of the chamber 1 to an exhaust pressure of atmosphere. The high compression pump 43 has several pumping or compressing stages, which successively compress the gases from the chamber 1 to atmospheric pressure. All of the pumping or compressing stages of the high compression pump 43 are disposed within one housing.

In the preferred embodiment, the high compression pump 43 compresses intake pressures of 10^{-1} to 10^{-5} Torr to exhaust pressures at atmospheric pressure. Alternatively, the high compression pump 43 compresses low intake pressures suitable for the process in the chamber 1 to atmospheric exhaust pressure.

The pressure in the chamber 1 is regulated by controlling the rotational frequency of the high compression pump 43 with the frequency signal f3. In the preferred embodiment, the controller 42 generates the frequency signal f3 as described above for the generation of the frequency signal f1 by the controller 9. In particular, the control rule for the controller 42 is a PID control rule, as discussed above for the first embodiment, and may include a gain scheduler, as discussed above for the first embodiment. Alternatively, the control rule may be any control rule useful for controlling the high compression pump 43. Similar to the embodiments described above, by varying the rotational frequency of the high compression pump 43, the pressure PHv of the chamber 1 is regulated.

The gauge or sensor 44 measures the pressure PCv internal to the high compression pump 43. Gauge or sensor 44 can produce an analog or digital signal. The signal from gauge or sensor 44 can be used to control the system according to a control rule or control rules in controller 42. Alternatively, additional internal or exhaust pressures of the high compression pump 43 can be measured by additional gauges or sensors 44.

In addition to or instead of regulating the pressure in the chamber 1 by controlling the rotational frequency of the high compression pump 43, any combination of the following can

be used: control valves 35, 36, 36, 39, and 40; any additional control valves for bypassing the compression stages of the high compression pump 43; the control valve 33; and any additional control valves for injecting gas into the compression stages of the high compression pump 43. Non-limiting examples of controlling the pressure in the chamber with control valves include any combination of the following: a control valve coupled between a compression stage and the exhaust side of the high compression pump 43; a control valve coupled between a compression stage and another compression stage of the high compression pump 43; a control valve coupled between a compression stage and the intake side of the high compression pump 43; a control valve coupled between the intake side and the exhaust side of the high compression pump 43; a control valve coupled between a compression stage and a gas supply and for injecting gas into the compression stage of the high compression pump 43; and a control valve coupled between the exhaust side of high compression pump 43 and a gas supply and for injecting gas into the exhaust side of the high compression pump 43.

To control any of the above combinations of control valves, one or more controllers can be used with one or more control rules and with any signal relevant to the control of the system. Non-limiting examples of a control rule or control rules include any combination of the following: a

threshold control rule, as described above for the first embodiment; a PID control rule, as described above for the first embodiment, and which may include a gain scheduler, as discussed above for the first embodiment; and a multi-variable control rule. Non-limiting examples of any signal relevant to the control of the system include any combination of the following: the pressure signal P; the set point pressure signal Ps; and a pressure signal corresponding to an internal or exhaust pressure of the high compression pump 43 as measured by the gauge or sensor 44.

In the several embodiments of the invention, several separate controllers are used to control various control valves and pumps in the system. Alternatively, a single controller can be used to control all the control valves and pumps in the system using a multi-variable control rule. In practicing the invention of the several embodiments, several controllers, a single controller, or any combination thereof can be used to control all the control valves and pumps in the system using a single control rule or multiple control rules. In practicing the invention, the controller or controllers can be either digital or analog and can implement a control rule or control rules in either discrete or continuous form.

As the invention has been described in detail with respect to the preferred embodiments, it will now be apparent from the foregoing to those skilled in the art that changes

and modifications may be made without departing from the invention in its broader aspects. The invention, therefore, as defined in the appended claims, is intended to cover all such changes and modifications as fall within the true spirit of the invention.

CLAIMS

WHAT IS CLAIMED IS:

1. An apparatus for regulating a pressure in a chamber comprising:

a first vacuum pump having a compression stage, an exhaust side, and an intake side communicating directly with the chamber for generating a first pressure in the chamber;

a controllable pressure regulator coupled to the first vacuum pump and having a control input for receiving a first signal for regulating an exhaust pressure at the exhaust side of the first vacuum pump or an internal pressure at the compression stage of the first vacuum pump, and to thereby regulate the pressure in the chamber; and

a controller having an input for receiving a second signal representing a control pressure in the apparatus, and an output connected to the control input of the controllable pressure regulator, the controller producing at the output the first signal as a function of the second signal.

2. An apparatus according to claim 1, wherein the controllable pressure regulator comprises:

a second vacuum pump having an intake side coupled to the exhaust side of the first vacuum pump and generating a second

pressure, higher than the first pressure, at the intake side of the second vacuum pump.

3. An apparatus according to claim 2, wherein the controllable pressure regulator further comprises:

a roots vacuum pump for coupling the first and second vacuum pumps and having a variable rotational frequency, an intake side coupled to the exhaust side of the first vacuum pump, and an exhaust side coupled to the intake side of the second vacuum pump, and wherein the first signal produced by the controller controls the variable rotational frequency of the roots vacuum pump and thereby regulates the exhaust pressure of the first vacuum pump.

4. An apparatus according to claim 2, wherein the controllable pressure regulator further comprises:

a controllable valve for coupling the first and second vacuum pumps and having an intake side coupled to the exhaust side of the first vacuum pump and an exhaust side coupled the intake side of the second vacuum pump.

5. An apparatus according to claim 4, wherein the first signal from the controller controls opening and closing of the controllable valve and thereby regulates the exhaust pressure of the first vacuum pump.

6. An apparatus according to claim 4, wherein the controllable pressure regulator further comprises:

a stepping motor for opening and closing the controllable valve, and wherein the first signal from the controller controls stepping of the stepping motor and thereby regulates the exhaust pressure of the first vacuum pump.

7. An apparatus according to claim 2, wherein the second vacuum pump has a variable rotational frequency, and wherein the first signal produced by the controller controls the variable rotational frequency of the second vacuum pump and thereby regulates the exhaust pressure of the first vacuum pump.

8. An apparatus according to claim 1, wherein the first pressure generated by the first vacuum pump is less than atmospheric pressure;

wherein the exhaust pressure of the first vacuum pump is at atmospheric pressure;

wherein the first vacuum pump has a variable rotational frequency and a control input for receiving the first signal for varying the rotational frequency of the first vacuum pump;

wherein the controller produces the first signal for varying the variable rotational frequency of the first vacuum pump; and

wherein the controllable pressure regulator passes the first signal from its control input to the control input of the first vacuum pump.

9. The apparatus according to claim 1, wherein the controllable pressure regulator comprises a controllable valve having an intake side coupled to a gas supply and an exhaust side coupled to the exhaust side of the first vacuum pump.

10. The apparatus according to claim 1, wherein the controllable pressure regulator comprises a controllable valve having an intake side coupled to a gas supply and an exhaust side coupled to the compression stage of the first vacuum pump.

11. The apparatus according to claim 1, wherein the controllable pressure regulator comprises a controllable valve having an intake side coupled to the compression stage of the first vacuum pump and an exhaust side coupled to the exhaust side of the first vacuum pump.

12. The apparatus according to claim 1, wherein the first vacuum pump has a second compression stage, and wherein the controllable pressure regulator comprises a controllable valve having an intake side coupled to the compression stage

of the first vacuum pump and an exhaust side coupled to the second compression stage of the first vacuum pump.

13. The apparatus according to claim 1, wherein the controllable pressure regulator comprises a controllable valve having an intake side coupled to the compression stage of the first vacuum pump and an exhaust side coupled to the intake side of the first vacuum pump.

14. The apparatus according to claim 1, wherein the controllable pressure regulator comprises a controllable valve having an intake side coupled to the intake side of the first vacuum pump and an exhaust side coupled to the exhaust side of the first vacuum pump.

15. The apparatus according to claim 1, wherein the controllable pressure regulator comprises:

a second vacuum pump having an intake side coupled to the exhaust side of the first vacuum pump;

a first controllable valve having an intake side coupled to the compression stage of the first vacuum pump and an exhaust side; and

a second controllable valve for coupling the first and second vacuum pumps and having an intake side coupled to the exhaust side of the first vacuum pump and an exhaust side

coupled to the intake side of the second vacuum pump and the exhaust side of the first controllable valve.

16. An apparatus according to claim 1, wherein the control pressure in the apparatus is the pressure in the chamber; and

wherein the controller receives at its input a third signal representing a desired pressure in the chamber; and

wherein the controller produces the first signal as a function of the second signal, the third signal, and a proportional-integral-derivative control rule.

17. An apparatus according to claim 16, wherein the proportional-integral-derivative control rule comprises a proportional gain, an integral gain, and a derivative gain.

18. An apparatus according to claim 17, wherein the derivative gain of the proportional-integral-derivative control rule is zero.

19. An apparatus according to claim 1, wherein the controller comprises:

a control rule having at least one gain, the control rule for producing the first signal; and

a gain scheduler for determining the at least one gain of the control rule.

20. An apparatus according to claim 19, wherein the control pressure in the apparatus is a desired pressure in the chamber;

wherein the gain scheduler comprises a plurality of gains; and

wherein the gain scheduler selects the at least one gain from the plurality of gains according to the second signal.

21. An apparatus according to claim 1, wherein the control pressure in the apparatus is a desired pressure in the chamber; and

wherein the controller produces the first signal as a function of a comparison between the second signal and a threshold value.

22. An apparatus according to claim 1, wherein the control pressure in the apparatus is the pressure in the chamber, a desired pressure in the chamber, the exhaust pressure at the exhaust side of the first vacuum pump, or the internal pressure at the compression stage of the first vacuum pump.

23. A method for regulating a pressure in a chamber, wherein a first vacuum pump has a compression stage, an exhaust side, and an intake side communicating directly with the chamber, comprising the steps of:

generating a first pressure in the chamber with the first vacuum pump; and

controlling an exhaust pressure at the exhaust side of the first vacuum pump or an internal pressure at the compression stage of the first vacuum pump as a function of a control pressure in the apparatus to thereby regulate the pressure in the chamber.

24. A method according to claim 23, wherein a second vacuum pump having an intake side is coupled to the exhaust side of the first vacuum pump, and further comprising the step of:

generating a second pressure, higher than the first pressure, at the intake side of the second vacuum pump.

25. A method according to claim 24, wherein a roots vacuum pump couples the first and second vacuum pumps and has a variable rotational frequency, and

wherein controlling the exhaust pressure comprises varying the variable rotational frequency of the roots vacuum pump.

26. A method according to claim 24, wherein a controllable valve couples the first and second vacuum pumps, and

wherein the step of controlling comprises opening and closing the controllable valve.

27. A method according to claim 24, wherein the second vacuum pump has a variable rotational frequency, and

wherein the step of controlling comprises varying the variable rotational frequency of the second vacuum pump.

28. A method according to claim 23, wherein the first pressure generated by the first vacuum pump is less than atmospheric pressure;

wherein the exhaust pressure of the first vacuum pump is at atmospheric pressure;

wherein the first vacuum pump has a variable rotational frequency; and

wherein the step of controlling comprises varying the variable rotational frequency of the first vacuum pump.

29. The apparatus according to claim 23, wherein a controllable valve has an intake side coupled to a gas supply and an exhaust side coupled to the exhaust side of the first vacuum pump, and

wherein the step of controlling comprises opening and closing the controllable valve.

30. The apparatus according to claim 23, wherein controllable valve has an intake side coupled to a gas supply and an exhaust side coupled to the compression stage of the first vacuum pump, and

wherein the step of controlling comprises opening and closing the controllable valve.

31. The apparatus according to claim 23, wherein a controllable valve has an intake side coupled to the compression stage of the first vacuum pump and an exhaust side coupled to the exhaust side of the first vacuum pump, and

wherein the step of controlling comprises opening and closing the controllable valve.

32. The apparatus according to claim 23, wherein the first vacuum pump has a second compression stage, and wherein a controllable valve has an intake side coupled to the compression stage of the first vacuum pump and an exhaust side coupled to the second compression stage of the first vacuum pump, and

wherein the step of controlling comprises opening and closing the controllable valve.

33. The apparatus according to claim 23, wherein controllable valve has an intake side coupled to the compression stage of the first vacuum pump and an exhaust side coupled to the intake side of the first vacuum pump, and

wherein the step of controlling comprises opening and closing the controllable valve.

34. The apparatus according to claim 23, wherein a controllable valve has an intake side coupled to the intake side of the first vacuum pump and an exhaust side coupled to the exhaust side of the first vacuum pump, and

wherein the step of controlling comprises opening and closing the controllable valve.

35. The apparatus according to claim 23, wherein a second vacuum pump has an intake side coupled to the exhaust side of the first vacuum pump;

wherein a first controllable valve has an intake side coupled to the compression stage of the first vacuum pump and an exhaust side; and

wherein a second controllable valve couples the first and second vacuum pumps and has an intake side coupled to the exhaust side of the first vacuum pump and an exhaust side coupled to the intake side of the second vacuum pump and the exhaust side of the first controllable valve; and

wherein the step of controlling comprises opening and closing the first and second controllable valves.

36. A method according to claim 23, wherein the control pressure in the apparatus is the pressure in the chamber; and

wherein the step of controlling comprises controlling the exhaust pressure at the exhaust side of the first vacuum pump or the internal pressure at the compression stage of the first vacuum pump as a function of the control pressure in the apparatus, a desired pressure in the chamber, and a proportional-integral-derivative control rule.

37. A method according to claim 36, wherein the proportional-integral-derivative control rule comprises a proportional gain, an integral gain, and a derivative gain.

38. An apparatus according to claim 37, wherein the derivative gain of the proportional-integral-derivative control rule is zero.

39. A method according to claim 23, wherein the control pressure in the apparatus is the pressure in the chamber; and

wherein the step of controlling comprises:

selecting at least one gain from a plurality of gains according to the control pressure in the apparatus;

controlling the exhaust pressure at the exhaust side of the first vaccum pump or the internal pressure at the compression stage of the first vacuum pump as a function of a control rule, the selected at least one gain, the control pressure of the apparatus, and a desired pressure in the chamber.

40. A method according to claim 23, wherein the control pressure in the apparatus is a desired pressure in the chamber; and

wherein the step of controlling comprises controlling the exhaust pressure at the exhaust side of the first vaccum pump or the internal pressure at the compression stage of the first vacuum pump as a function of the control pressure in the apparatus and a comparison between the control pressure in the apparatus and a threshold value.

41. A method according to claim 23, wherein the control pressure in the apparatus is the pressure in the chamber, a desired pressure in the chamber, the exhaust pressure at the exhaust side of the first vacuum pump, or the internal pressure at the compression stage of the first vacuum pump.

ABSTRACT OF THE DISCLOSURE

A pressure for a chamber is regulated by controlling either the exhaust pressure at the exhaust side of a first vacuum pump or the internal pressure at a compression stage of the first vacuum pump, where the first vacuum pump is directly communicating with the chamber. The pressure of the chamber can be regulated by combinations of the following: controlling the variable rotational frequency of a roots vacuum pump, a pre-vacuum pump, or a high compression pump; controlling a control valve between a pre-vacuum pump and the first vacuum pump; controlling a control valve for injecting gas into the exhaust side of the first vacuum pump or into the compression stage of the first vacuum pump; and controlling a control valve or control valves for bypassing the first vacuum pump or a compression stage or compression stages of the first vacuum pump. To regulate the pressure in the chamber, several types of control rules can be used, including: a PID control rule, a gain scheduler, and a threshold comparison control rule.

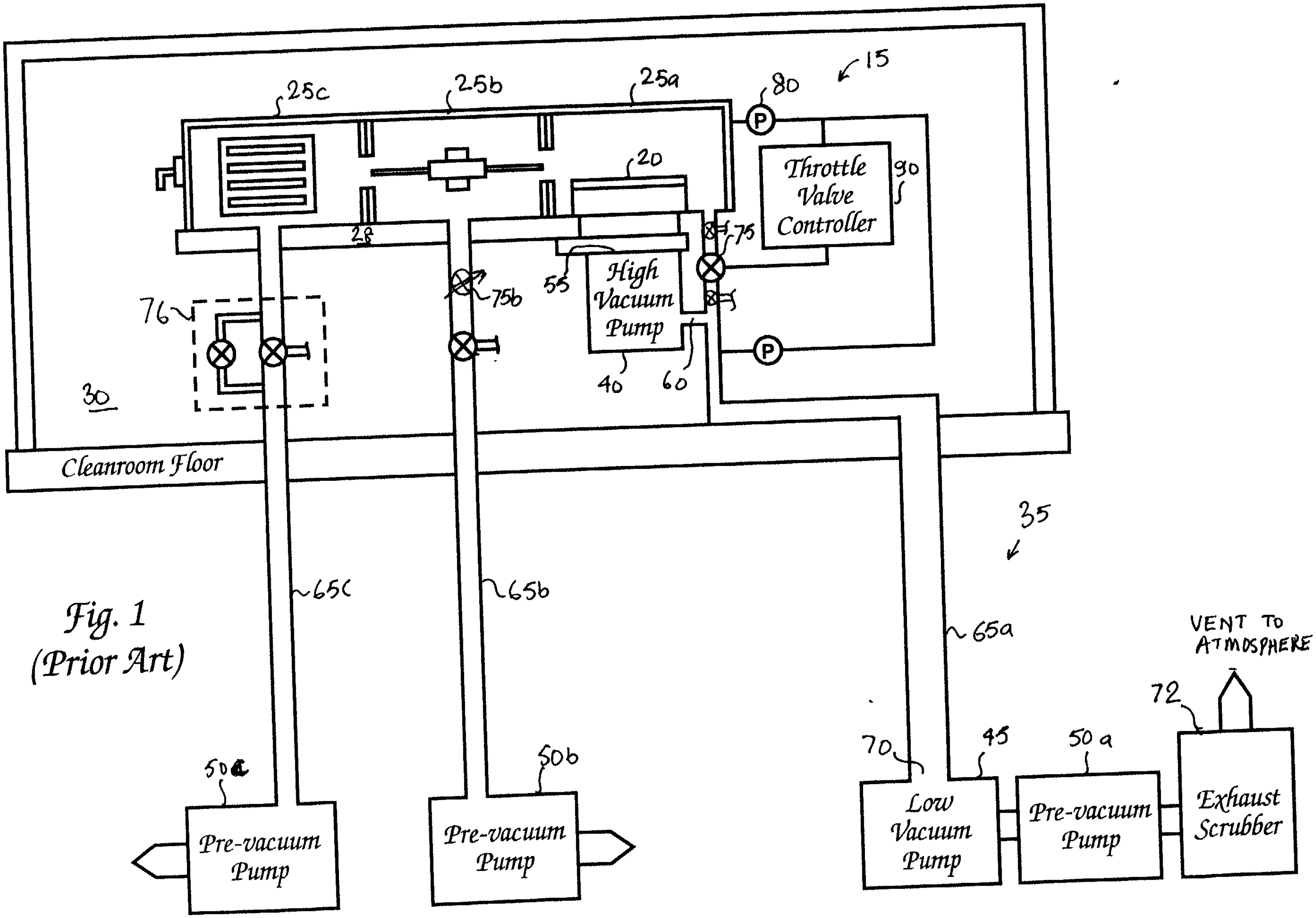
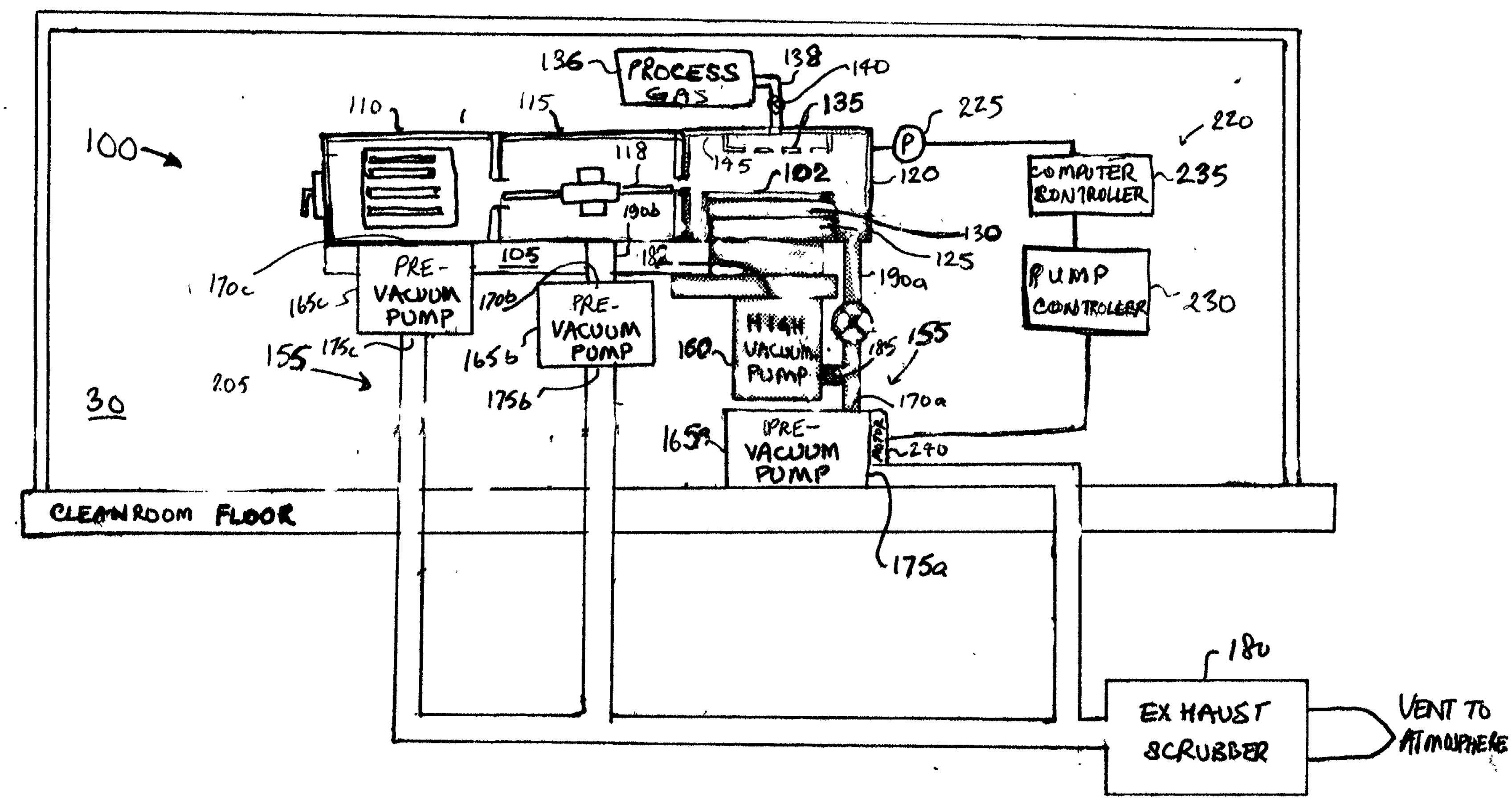


Fig. 1
(Prior Art)



100
110
115
118
136
PROCESS GAS
138
140
135
225
P
220
145
102
120
COMPUTER CONTROLLER
235
190b
130
125
105
182
190a
170c
165c
PRE-VACUUM PUMP
170b
PRE-VACUUM PUMP
HIGH VACUUM PUMP
PUMP CONTROLLER
230
155
175c
165b
160
185
155
205
175b
170a
30
165a
PRE-VACUUM PUMP
240
CLEANROOM FLOOR
175a
180
EXHAUST SCRUBBER
VENT TO ATMOSPHERE

FIG. 2

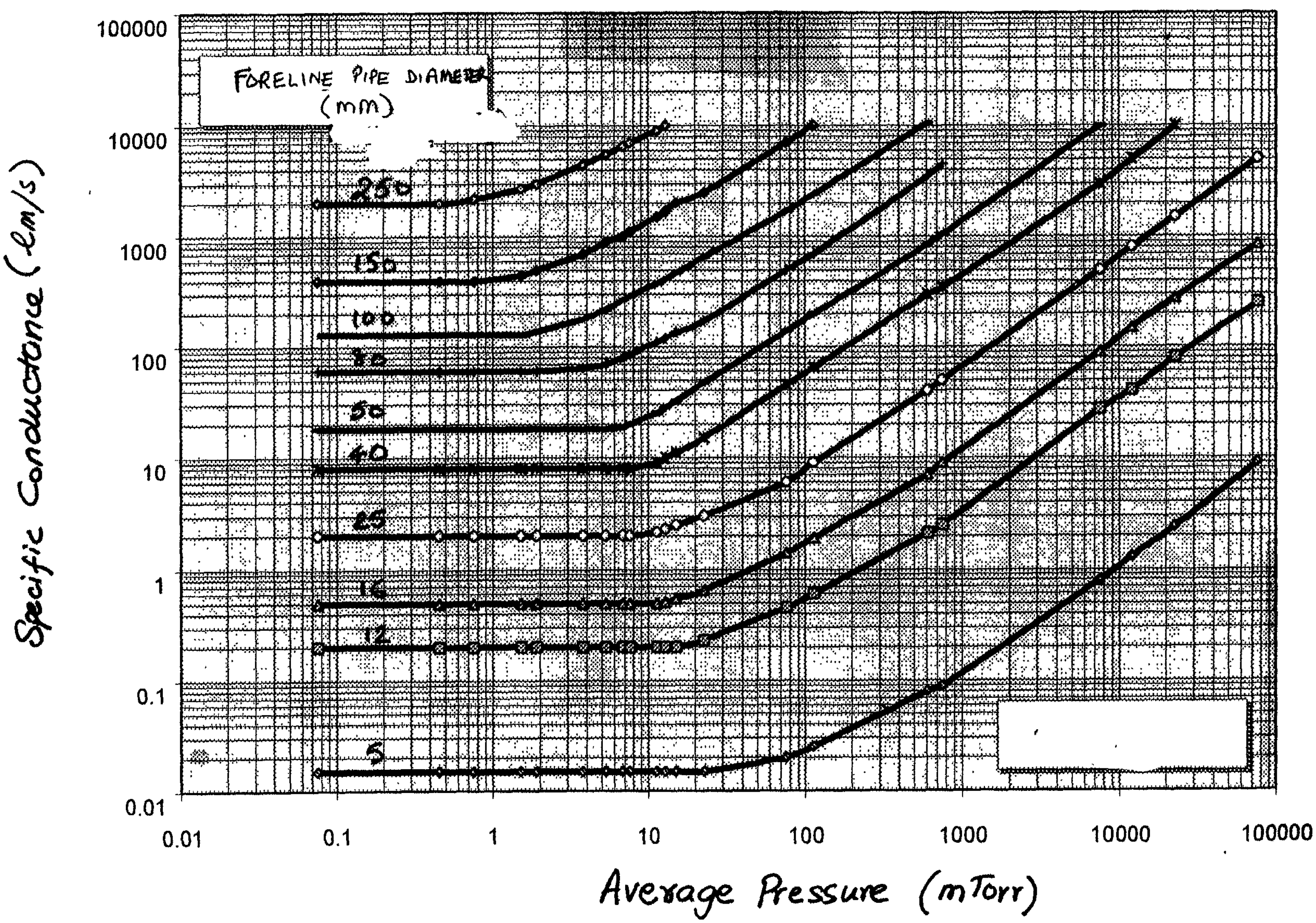

FORELINE PIPE DIAMETER (mm)
250
150
100
80
50
40
25
16
12
5
100000
10000
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
1000
10000
100000
Specific Conductance (ℓm/s)
Average Pressure (mTorr)

FIG. 3

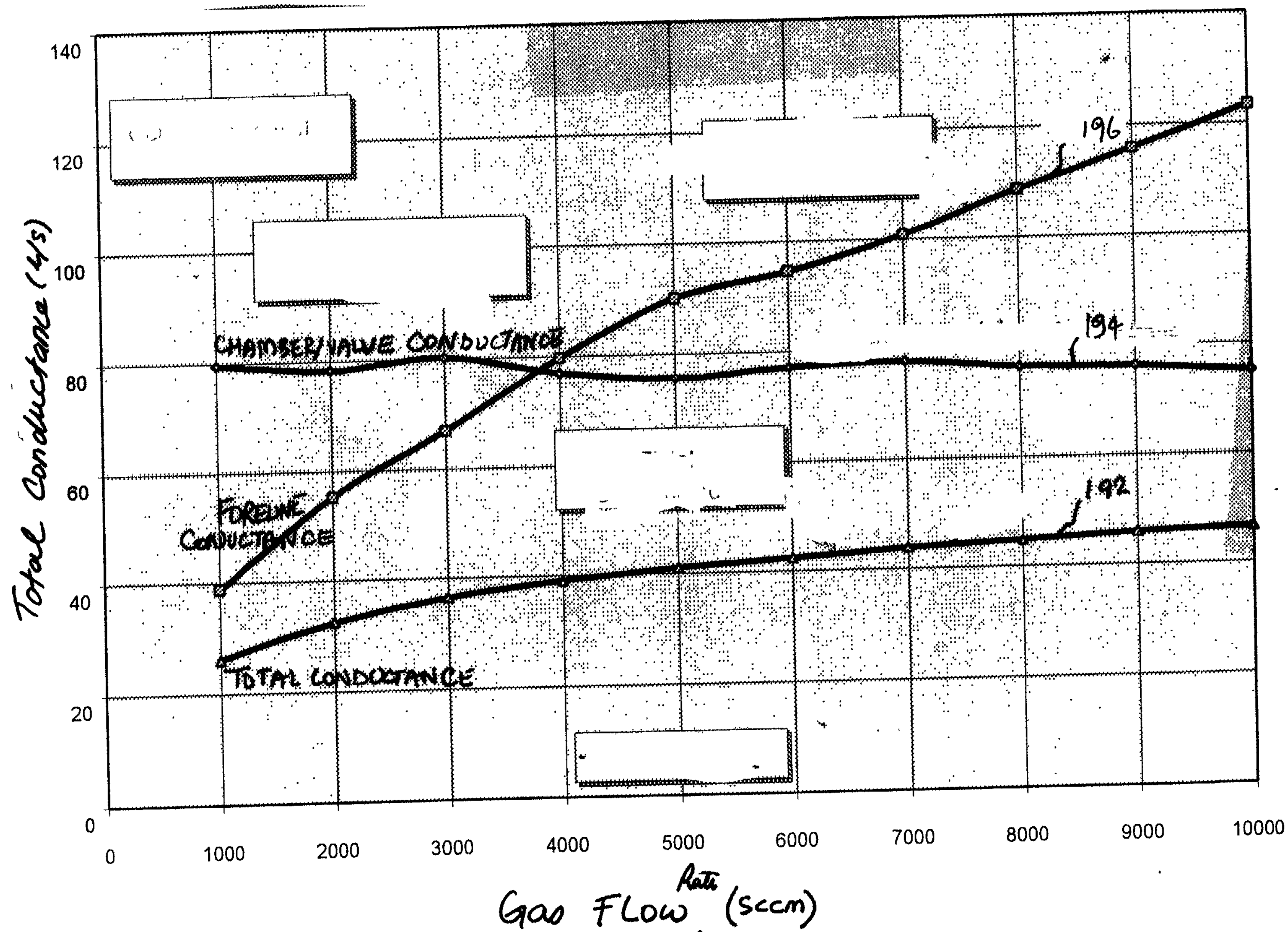
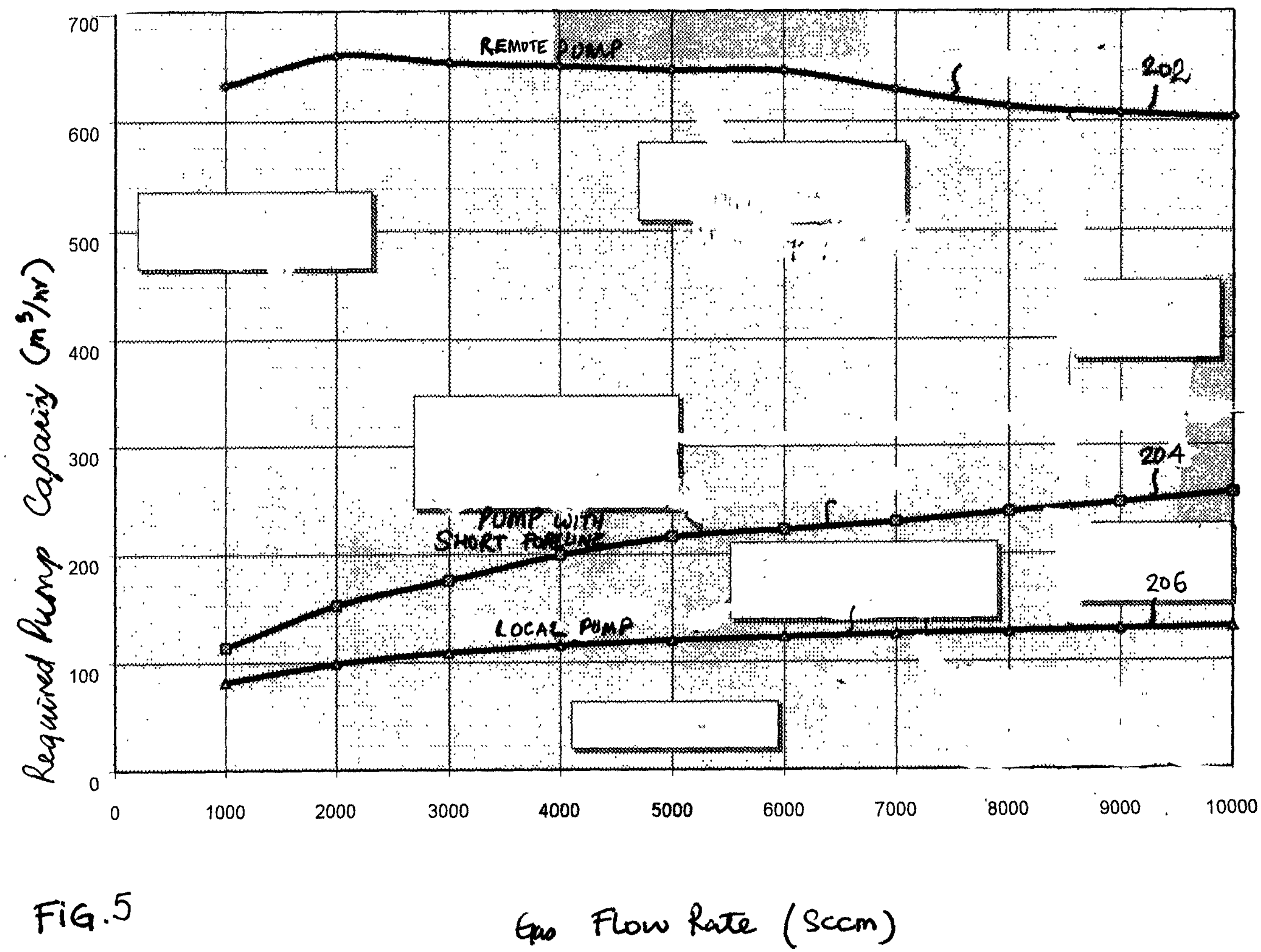
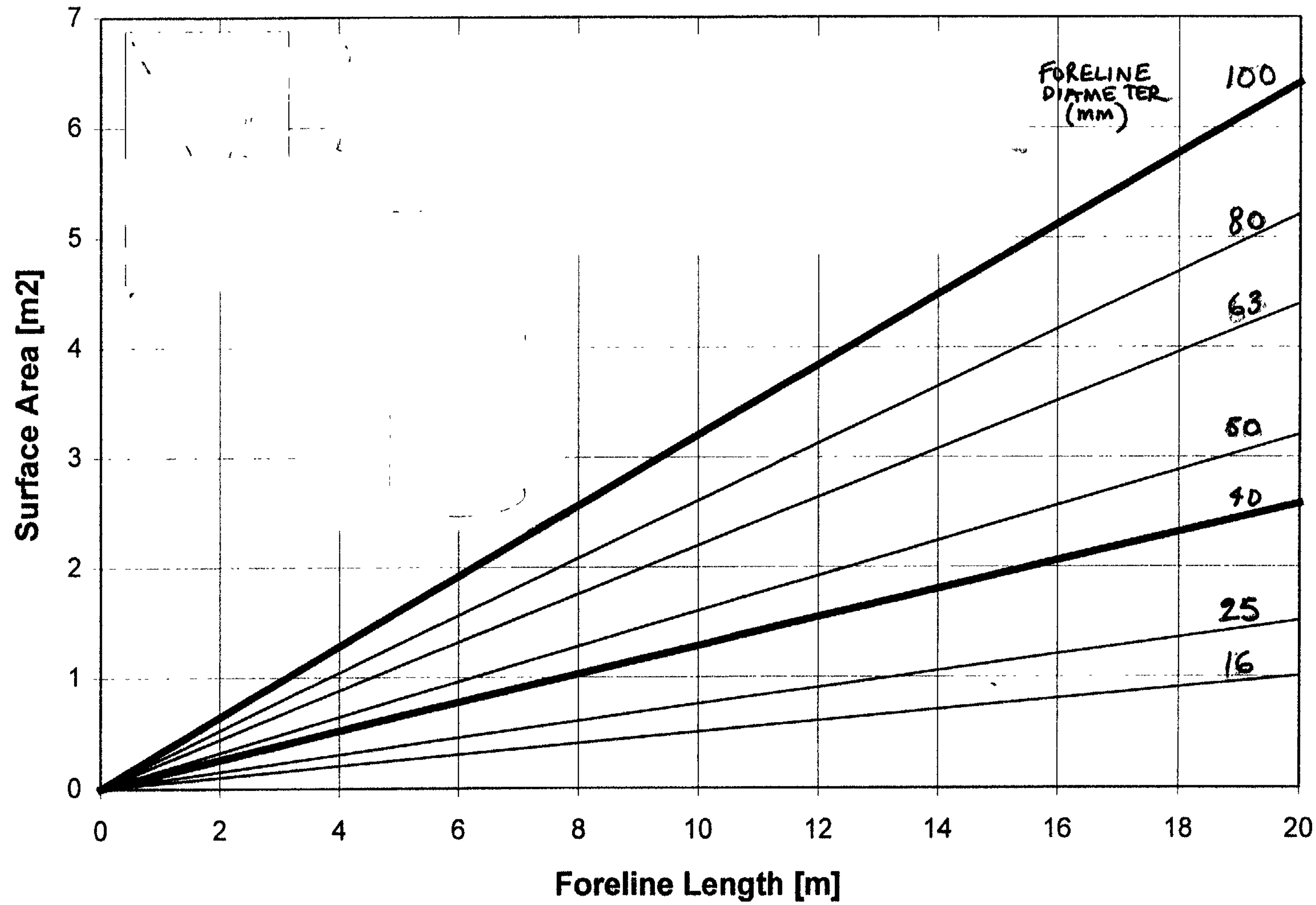

140
120
100
80
60
40
20
0
Total Conductance (l/s)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Gas Flow Rate (sccm)
CHAMBER/VALVE CONDUCTANCE
FORELINE CONDUCTANCE
TOTAL CONDUCTANCE
196
194
192

FIG 4



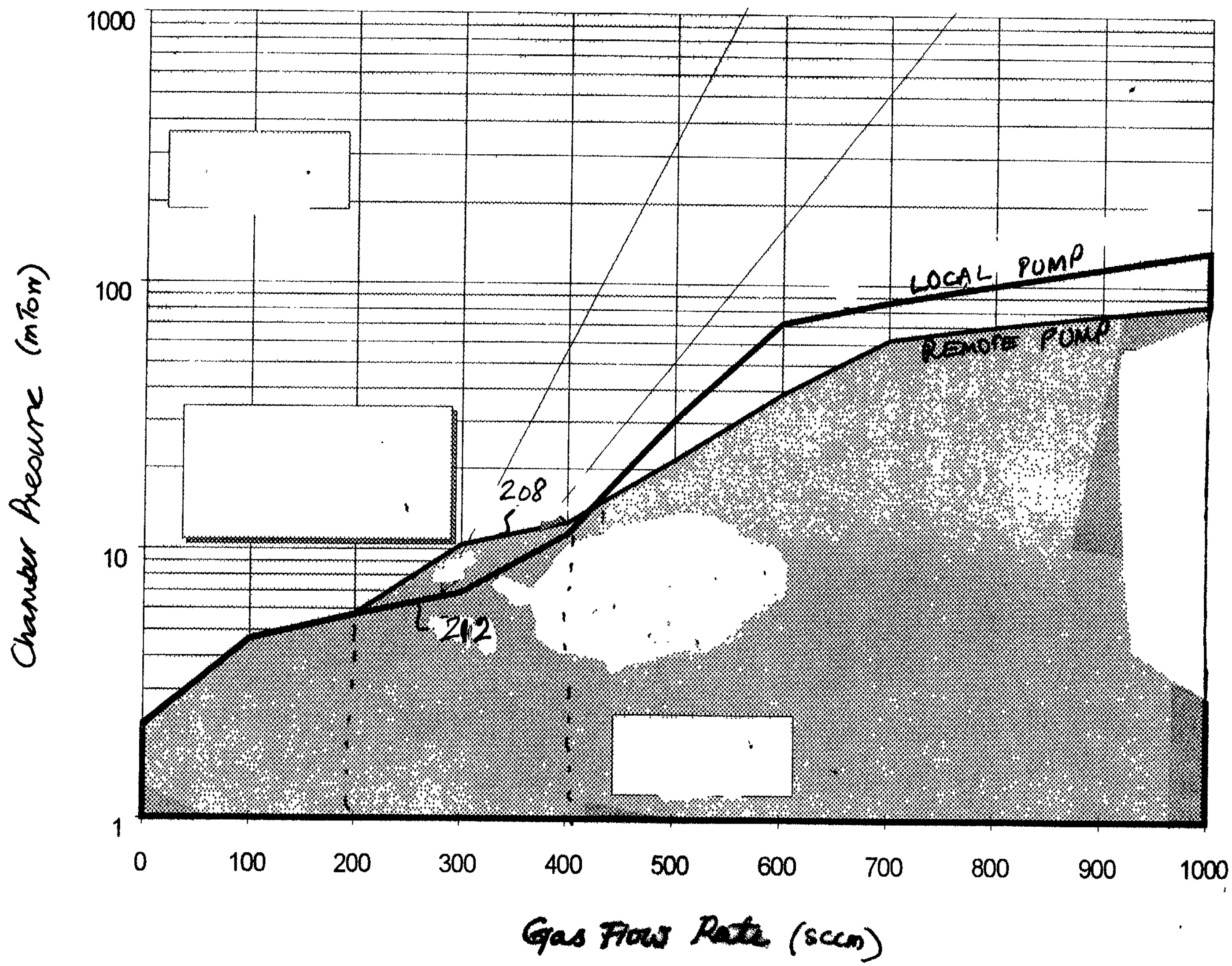
REMOTE PUMP
PUMP WITH SHORT FORELINE
LOCAL PUMP
202
204
206
Required Pump Capacity (m³/hr)
Gas Flow Rate (Sccm)

FIG. 5



Surface Area [m2]
Foreline Length [m]
FORELINE DIAMETER (mm)
100
80
63
50
40
25
16

FIG. 6



1000
100
10
1
0
100
200
300
400
500
600
700
800
900
1000
Chamber Pressure (mTorr)
Gas Flow Rate (sccm)
LOCAL PUMP
REMOTE PUMP
208
212

FIG 7

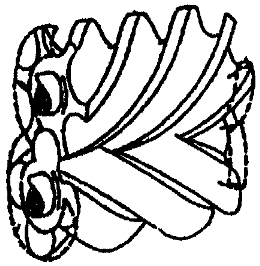


Fig 8a

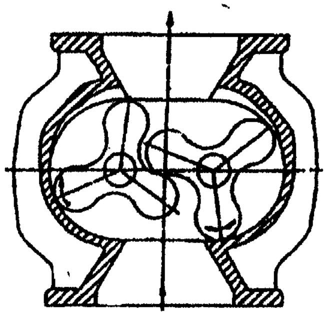


Fig 8b

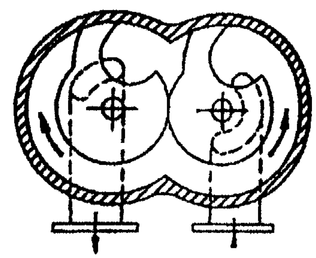


Fig 8c

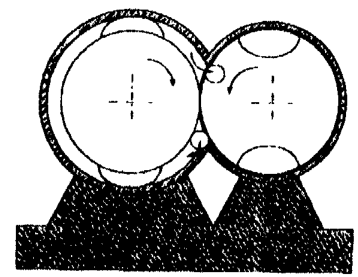


Fig 8d

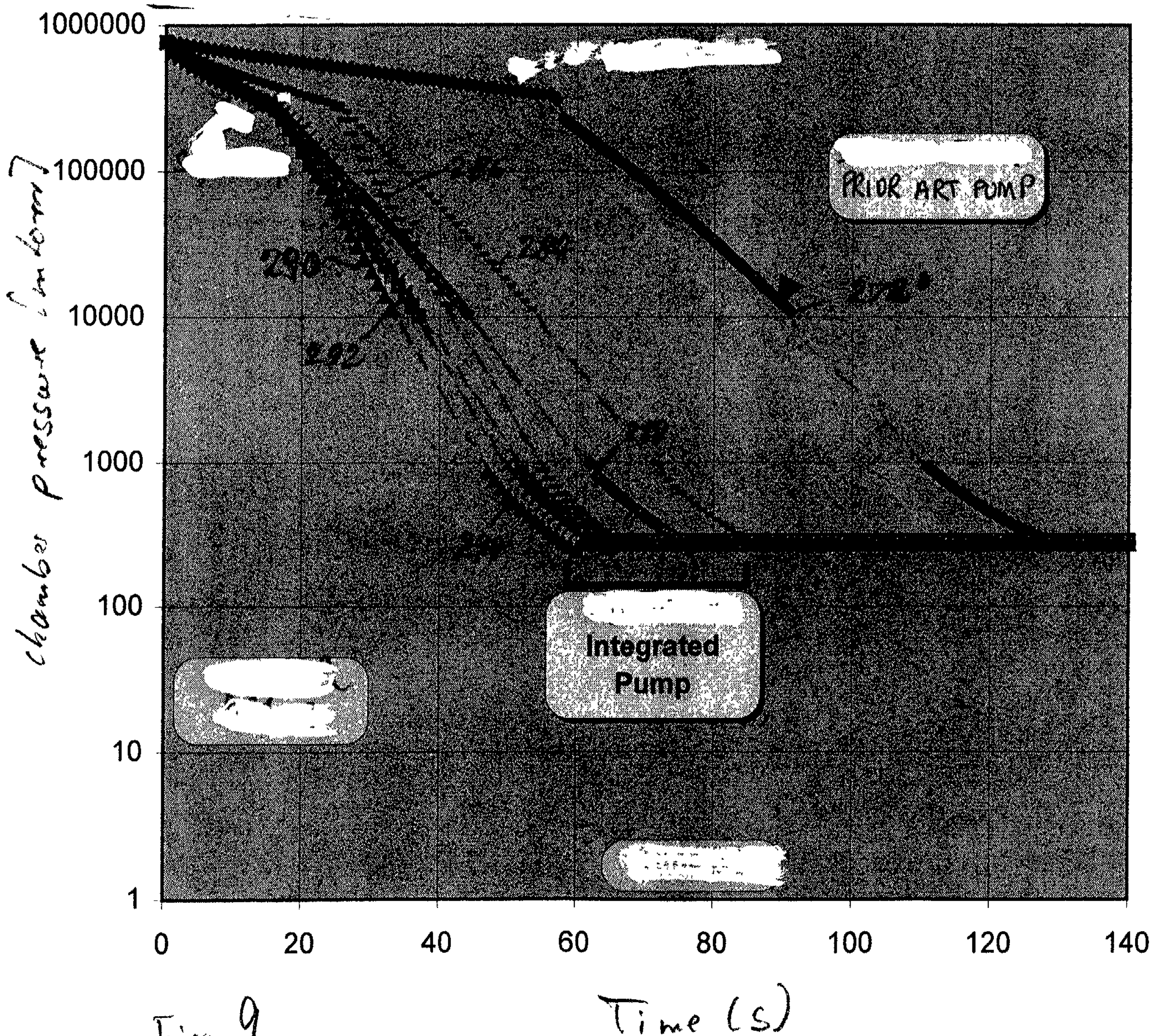

1000000
100000
10000
1000
100
10
1
0
20
40
60
80
100
120
140
chamber pressure
Time (s)
PRIOR ART PUMP
Integrated
Pump
290
292

Fig. 9

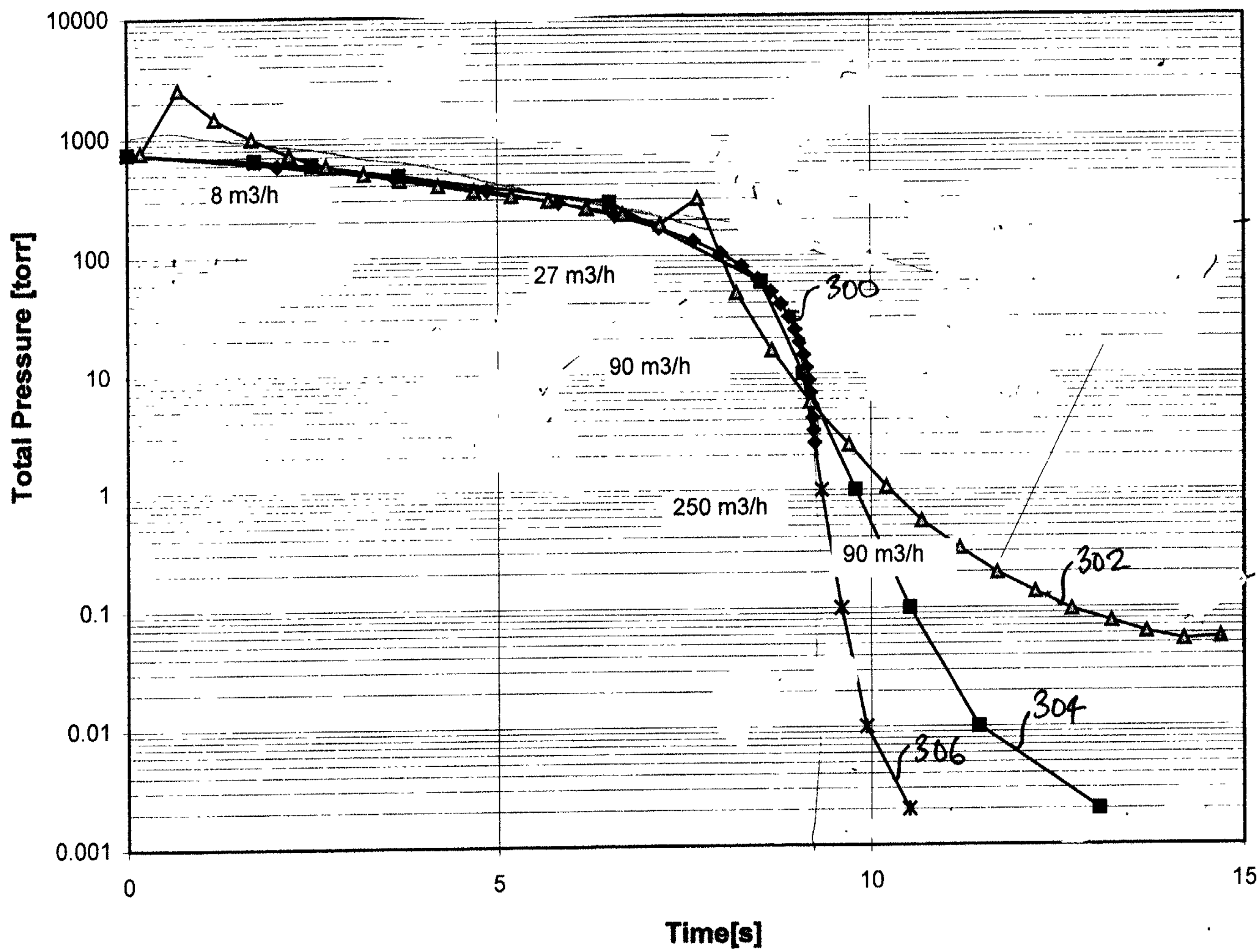
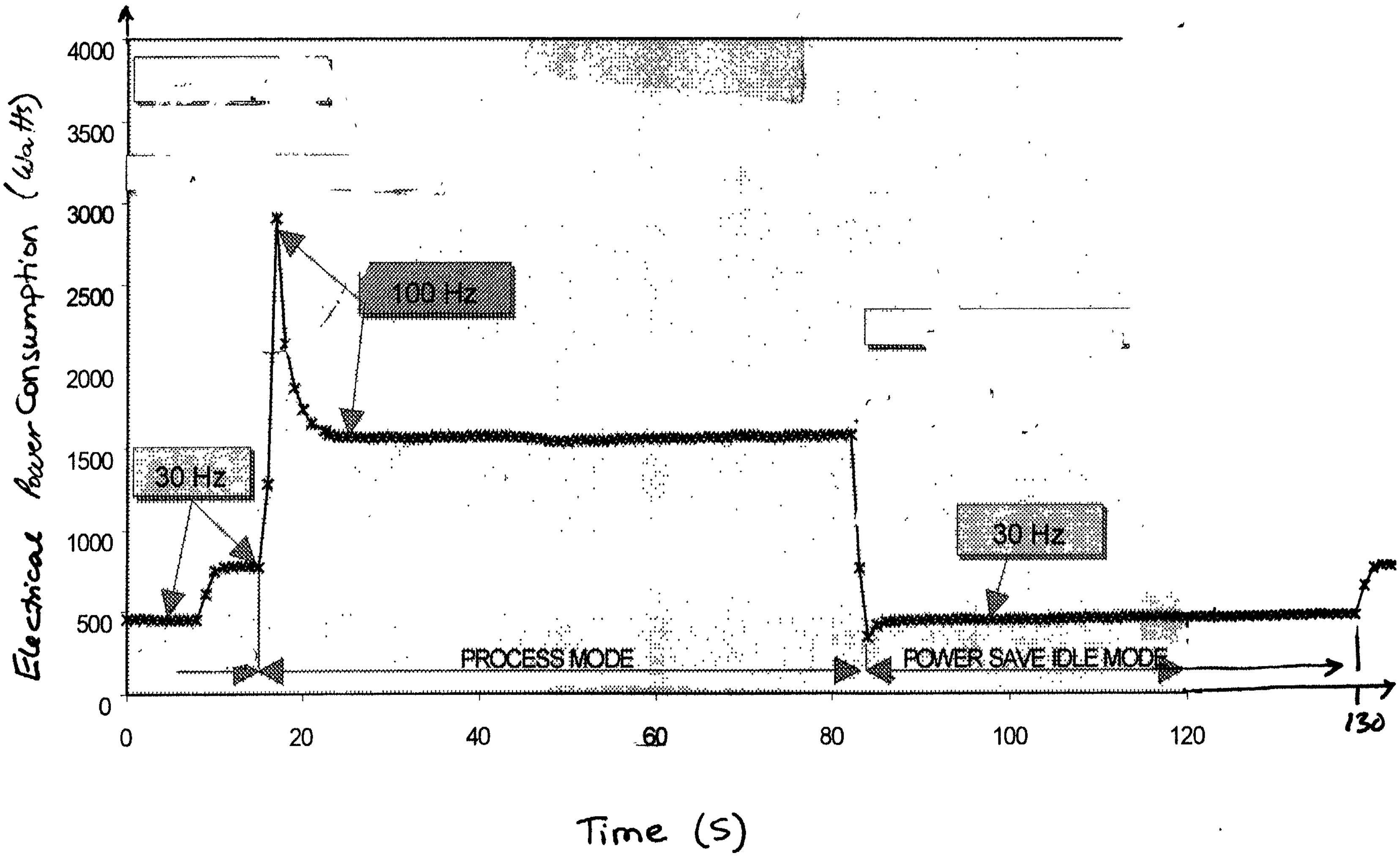

Total Pressure [torr]
10000
1000
100
10
1
0.1
0.01
0.001
0
5
10
15
Time[s]
8 m3/h
27 m3/h
90 m3/h
250 m3/h
90 m3/h
300
302
304
306

FIG 10.



Electrical Power Consumption (Watts)
4000
3500
3000
2500
2000
1500
1000
500
0
0
20
40
60
80
100
120
130
100 Hz
30 Hz
30 Hz
PROCESS MODE
POWER SAVE IDLE MODE
Time (s)

Fig 11

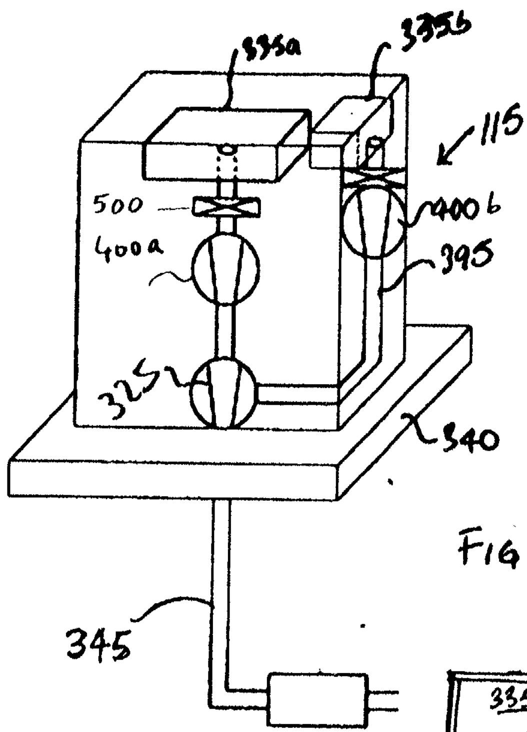


Fig 12a

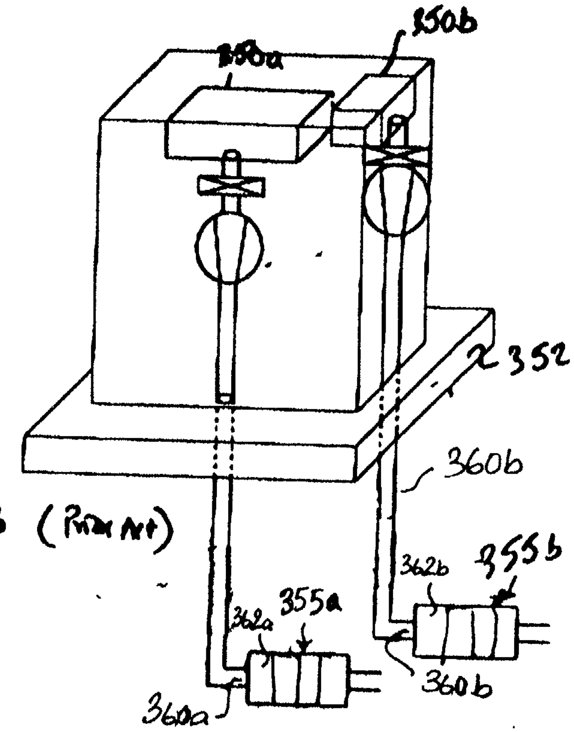


Fig 13 (Prior Art)

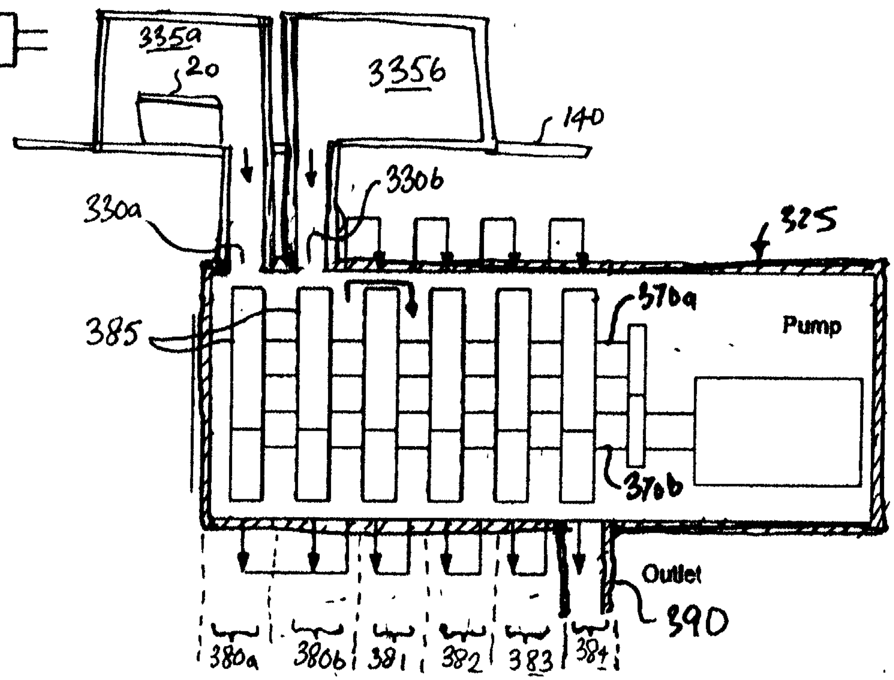


Fig 12b.